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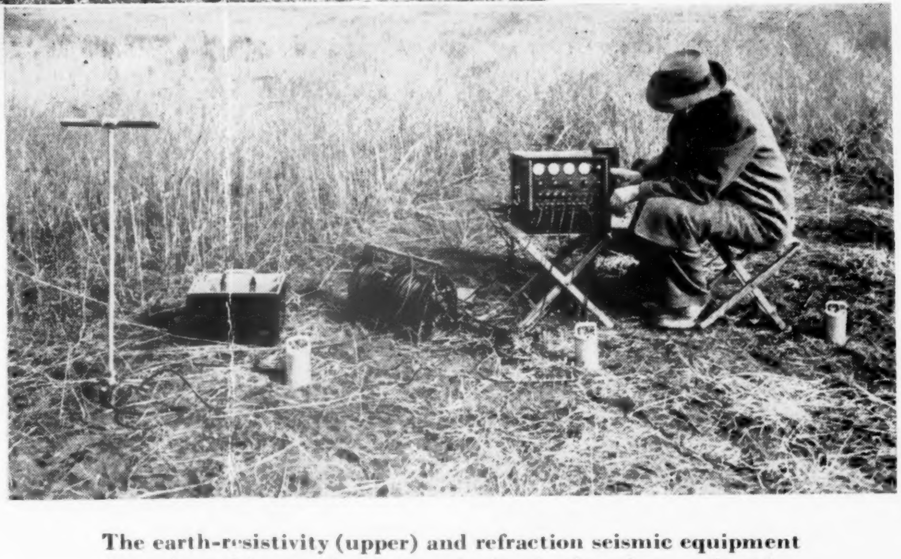

The earth-resistivity (upper) and refraction seismic equipment (lower) used in geophysical methods of subsurface exploration

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BUREAU OF PUBLIC ROADS

U. S. DEPARTMENT OF COMMERCE

E. A. STROMBERG, Editor

Geophysical Methods of Subsurface Exploration in Highway Construction

BY THE PHYSICAL RESEARCH BRANCH
BUREAU OF PUBLIC ROADS

Reported [1] by R. WOODWARD MOORE, Highway Engineer

Geophysical methods of subsurface exploration have been employed in various fields of engineering for more than 20 years. Since 1933 the Bureau of Public Roads has been studying the application of these methods to highway work, and has found that earth-resistivity and refraction seismic tests are well adapted to road construction problems. The Bureau has designed and built portable equipment for both types of test, which were described in PUBLIC ROADS in 1935.

Subsequent work, carried on during the past 15 years in 21 States, has established both methods as useful, rapid, and economical means of obtaining preliminary information on the depth and nature of subsurface formations. In this article are presented a review of the theory and method of operation of the two types of equipment, and the results of a number of actual field surveys made with them.

It will be evident from these data that, while both geophysical exploration methods are useful, the earth-resistivity test is more universally applicable to a variety of highway construction problems than the refraction seismic test. Detailed subsurface surveys can best be made by initial use of the resistivity equipment, followed by check tests with the seismic apparatus where needed. Since the fundamental principles of the two methods differ widely, concordant data from both may be accepted with considerable assurance.

SINCE 1933 the Bureau of Public Roads has had in progress a study of geophysical methods of subsurface exploration as applied to highway engineering problems, including the development of instruments and of methods of interpretation of the data obtained. Early progress was reported in papers published in 1935 (*15*) [2] and in 1936 (*17*). Both earth-resistivity and refraction seismic apparatus were adapted or developed for use in the shallow subsurface explorations usually associated with highway construction. Special attention was given to the necessity for portable units capable of being transported by hand into areas where reconnaissance surveys might be required. The cover illustrations show the earth-resistivity apparatus and the seismic equipment now in use.

A large amount of data has been obtained by the Bureau of Public Roads with this equipment applied to such problems as slope design, classification of excavation materials on grading projects, foundation studies for bridges, buildings, and other structures, investigation of tunnel sites, location of sand, gravel, solid rock, and special soils for use in construction, determination of depth of peat and muck in swampy areas, and studies of existing and potential slide areas. These field studies have been carried out in 21 States.[3]

Summary

Despite limitations that are enumerated in this article, and others which may arise in future exploration work, the geophysical methods of test have definitely established their value in connection with highway work, particularly for use in preliminary surveys. Their use by the Bureau of Public Roads and other Federal and State agencies has emphasized the value of these relatively inexpensive methods of shallow subsurface exploration in obtaining information to be used for design purposes or as control for more detailed subsurface surveys by core drilling and other commonly used direct methods. The fundamental principles of the two methods differ so widely that where both methods give concordant data they may be accepted with considerable assurance. When they are used jointly at a given location, a limited amount of confirming data from seismic tests can serve as a valuable check on a considerable number of the more inexpensive resistivity tests, at times obviating the need for test pits or auger holes for locating and identifying subsurface formations. This does not imply that test pits or auger holes may not be necessary for obtaining samples of soil and other materials for determination of their physical and other properties.

Even though there might exist some uncertainty that the geophysical methods of test would prove applicable to a particular subsurface condition, the simplicity, low cost, and rapidity with which the tests can be made recommend their trial before resorting to the more costly and tedious methods of direct exploration ofttimes employed.

Present Use

World War II caused curtailment of the use of the geophysical methods of exploration, with the general decrease in civilian construction, but an increased interest is being manifested at the present time. The New York State Department of Public Works has purchased equipment of both types and has assigned personnel to a continuing program of geophysical tests, since early in 1948, as a part of a regularly instituted program of subsurface exploration. The Pennsylvania Turnpike Commission has kept two earth-resistivity parties in the field since July 1948 in a systematic resistivity survey of well over 100 miles of right-of-way for extensions to the present Turnpike. The Michigan State Highway Department has purchased resistivity apparatus for use in locating construction materials and on other construction and maintenance problems. The Massachusetts State Department of Public Works has had in progress since 1944 a program involving the use of refraction seismic tests in studies of highway grading projects and structure sites (*29*). Wisconsin, Minnesota, Missouri, California, Texas, and Illinois have each had some experience in the application of earth-resistivity tests to highway construction problems (*5, 9, 10, 14*). The State highway departments of Georgia and Arkansas have expressed an active interest in an early application of earth-resistivity tests to their construction problems.

As a result of demonstration work done in New York, Connecticut, and New Hampshire, the Corps of Engineers of the Department of the Army adopted the seismic test as a more or less standard procedure in preliminary subsurface explorations in connection with investigations of possible dam sites for flood control. Hundreds of dam sites have been

[1] Presented at the twenty-ninth annual meeting of the Highway Research Board in Washington, D. C., December 1949.

[2] Italic numbers in parentheses refer to the chronologically arranged bibliography, p. 64.

[3] Arkansas, California, Colorado, Connecticut, Florida, Georgia, Idaho, Iowa, Maryland, Michigan, Missouri, Montana, New Hampshire, New Jersey, New York, North Carolina, Oregon, Pennsylvania, Tennessee, Virginia, Washington, and the District of Columbia.

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investigated by this method since the latter part of 1938 (*19, 21, 23*).

With this brief summary of the present status of geophysics as an integral part of our highway construction program, it may be of interest to review briefly the theoretical aspects of the two methods of test and to consider in more detail their application in the field.

Theory of Refraction Seismic Method

The seismic method of subsurface exploration[4] consists of creating sound or vibration waves within the earth, usually by exploding small charges of dynamite buried 3 or 4 feet beneath the surface, and measuring the time of travel of these waves from their point of origin to each of several detectors placed at known distances from the source. The variations in mechanical energy transmitted to the detectors are converted into variations in electrical energy which, in turn, are used to deflect light rays reflected from small mirrors that are parts of sensitive galvanometers, and these deflections are recorded photographically on rapidly moving film. Electrical circuits are so arranged as to obtain one impulse at the instant of firing the explosion shot and another as the first wave reaches each detector. Figure 1 shows three typical seismic records, the small break in the right-hand trace on each film indicating the start of the wave and the three separate breaks in the three traces on each of the films indicating the arrival of the wave front at each detector. Each space between the transverse lines on the film corresponds to a time interval of

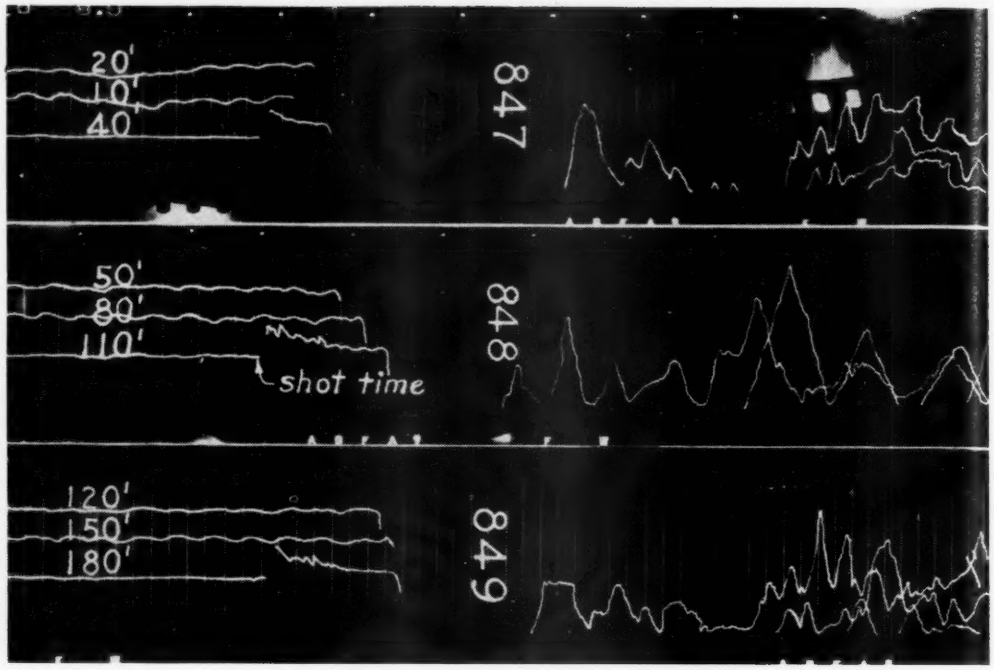


Figure 1.—Typical seismic film records.

0.005 second. It is usually possible to estimate to one-tenth part of this time interval.

The time lines are registered on the film by means of a suitably placed light source and a tuning fork operating at 100 cycles per second. Each tine of the tuning fork is equipped with thin phosphor-bronze plates having narrow slots which permit 200 flashes of light to reach the film during each second of time.

The time data obtained from film records and the measured distances along the ground surface between the shot point and the detectors are plotted in the form of time-distance graphs. From these the depth and probable character of the various subsurface formations are determined. Wave velocities range from approximately 600 feet per second in light loose soils to about 18,000 to 20,000 feet per second in dense, solid rock. This wide range in wave velocities makes possible a determination of the general character of the materials encountered, and by use of simple formulas the average depth to the various substrata can be calculated. A knowledge of the local geology helps materially in a more accurate identification of the formations encountered.

[4] For a more detailed description of the apparatus see reference (*15*). For additional discussion of the interpretation of refraction seismic data, together with their application to various field problems, see references (*19, 21, 23*).

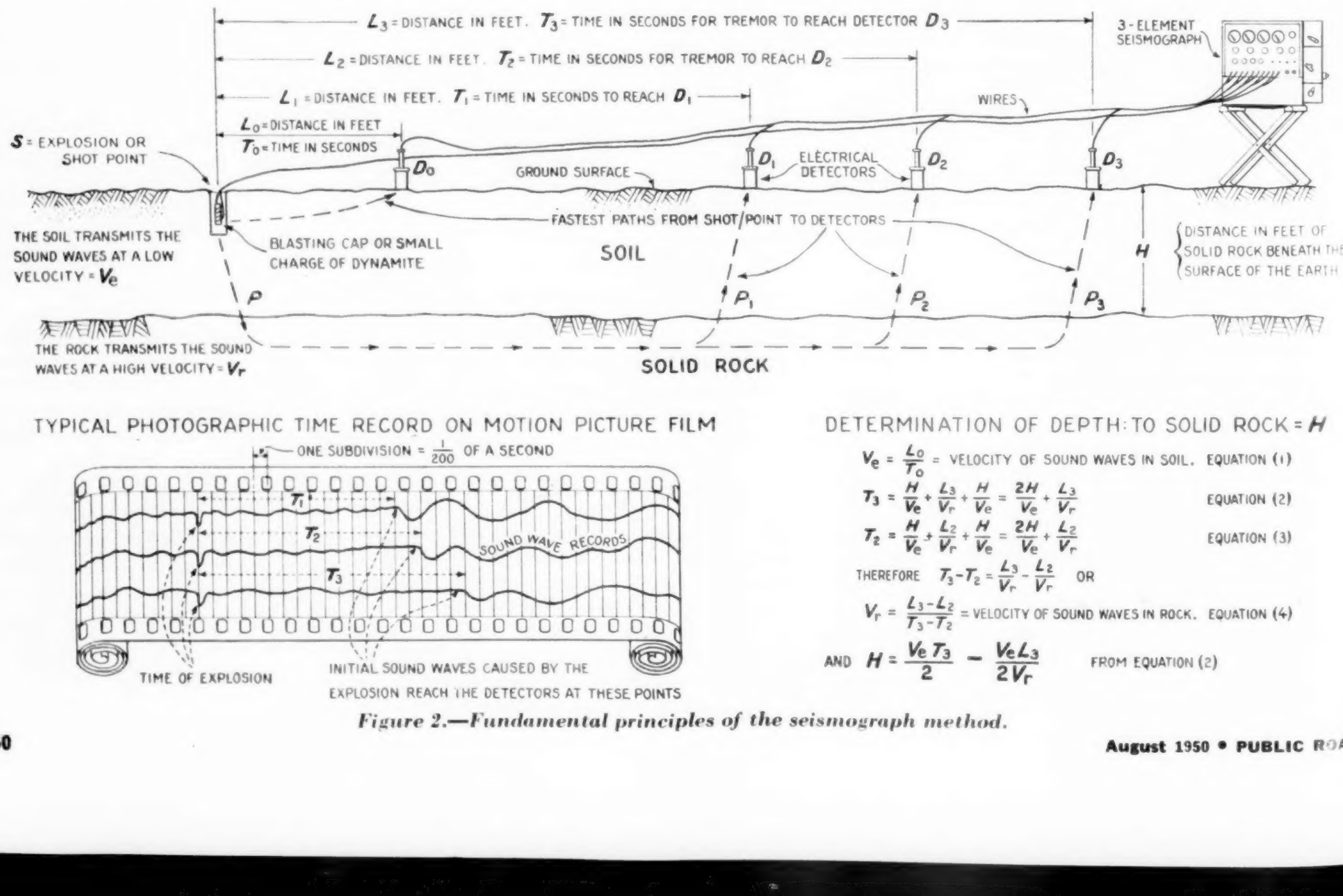


Figure 2.—Fundamental principles of the seismograph method.

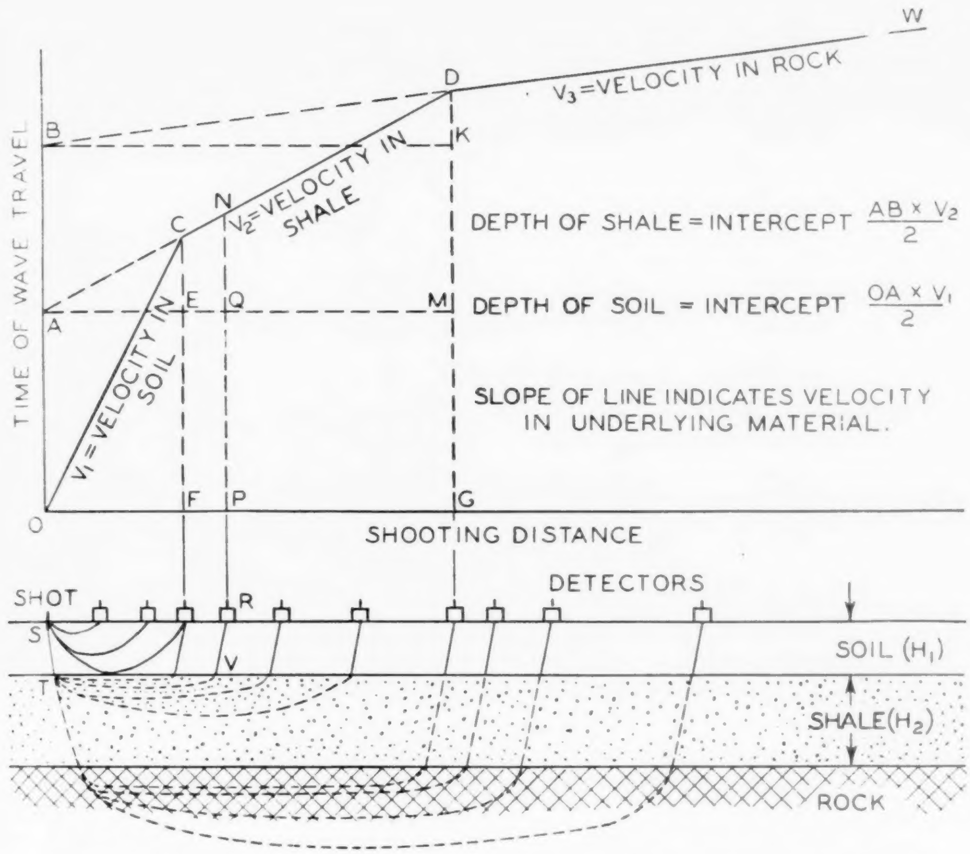


Figure 3.—Time-distance curve from which soil profile determinations are made.

Explanation of theory

The theory of refraction shooting and the derivation of approximate working formulas for depth determinations are shown in figure 2. The equations are developed on the assumption that the path of the seismic wave is vertically downward from the shot point to the rock or other dense stratum, thence along the rock to a point directly beneath the detector, and thence vertically upward to the detector. Although this assumption gives satisfactory values for the shallow depths involved in most highway problems, it is preferable to use a more exact formula for tests to greater depths such as are encountered in exploring locations for dams and certain other structures. The derivation and application of these formulas may be found in published papers (*18, 19*).

Although four detectors are shown in figure 2 to illustrate wave travel for the short distances involving the low-velocity soil and for the longer distances in the rock stratum, only three detectors are required for the three-channel seismograph used by the Bureau of Public Roads. The usual procedure, when using this type of equipment, is to place the three detectors on the ground in a line and at intervals of 25 to 50 feet apart. Shots are then fired successively at increasing distances along the extension of the line of detectors, beginning with a point 10 or 15 feet from the center detector and extending the shooting distance by increasing increments—for example, 50, 85, 125, 165, 225, and 300 feet from the center detector. There is an approximate relation between shot distance and the effective depth of the test such that this depth is about equal to one-third the shot distance. The relation depends somewhat on the relative wave velocities in the materials involved. If the depth to rock were more than about 80 feet, additional shot distances greater than the 300 feet mentioned above would be required to show a rock formation adequately. A duplicate line of shots is usually placed in the opposite direction from the center detector, expanding the data to allow depth determinations to be made when the interface between the overburden and the rock is not parallel to the surface but on a slope.

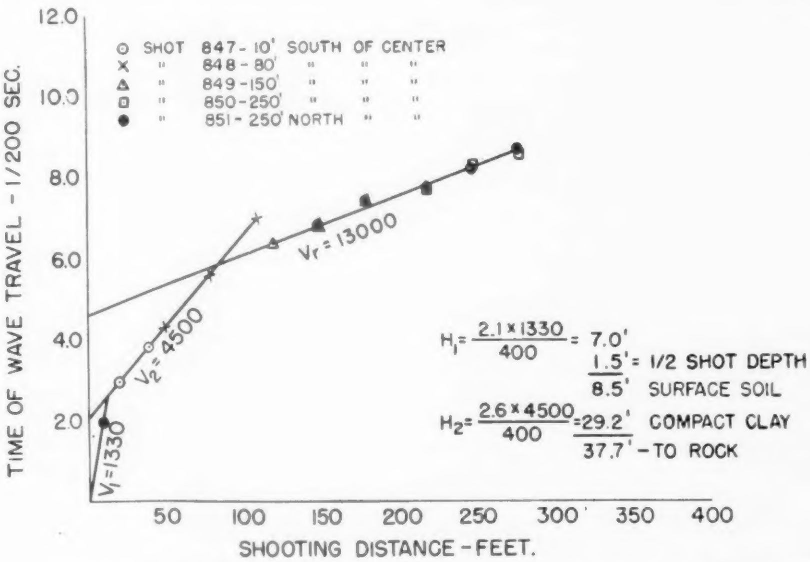


Figure 4.—Time-distance graph for seismic records shown in figure 1.

Time-distance curve

A theoretical time-distance curve is illustrated in figure 3. As shown, a straight line through the origin will result so long as a uniform homogeneous material comprises the surface layer. The velocity of wave propagation is constant in such a medium and time of wave travel is proportional to travel distance. The reciprocal of the slope of the line *OC*, passing through the origin, represents the velocity in the medium, V_1, since velocity is equal to distance divided by time.

If, at some greater depth, a second layer of homogeneous material of greater density is present, such as that designated as shale, there will be a point *F* at which there is a simultaneous arrival of a relatively slow wave through the less dense surface soil and one traveling over the longer but faster route along the top of the shale stratum. Beyond this critical distance *OF* a new slope *CD* exists, the reciprocal of which represents the faster wave travel in the shale, V_2; and for a path *STVR* the time *PQ* or *OA* is that required for the wave to travel through the surface soil from *S* to *T* and again from *V* to *R*. *QN* represents the time of travel from *T* to *V* in the shale. If H_1 is the thickness of the surface soil, we have the relation

$$H_1 = \frac{V_1 \times OA}{2}$$

Similarly, for a third layer having an even greater density, such as that designated as rock, there will be a second critical distance *OG*, and a second break in the curve to a new slope *DW*, the reciprocal of which will give the velocity V_3 in the rock. The time intercept *MK* or *AB* in this instance represents the time required for the wave to travel down through the shale and back again. If H_2 is the thickness of the shale then

$$H_2 = \frac{V_2 \times AB}{2}$$

In plotting the time-distance data the time units of 1/200 second, as taken directly from the

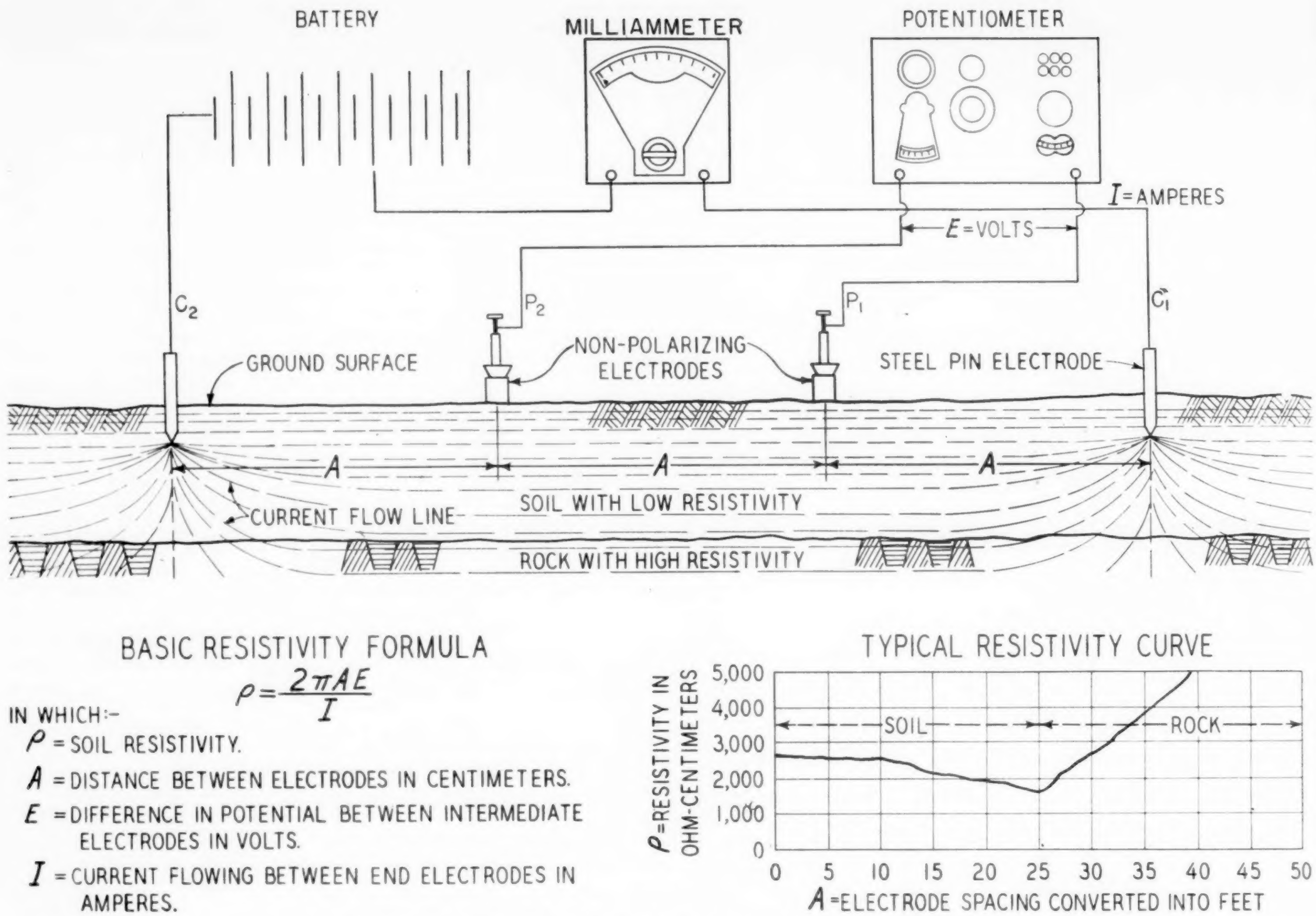


Figure 5.—Fundamental principles of the earth-resistivity method.

film records, are usually used; and the denominator in the foregoing equations becomes 400 instead of 2.

When the geologic conditions existing at a particular test location actually approach those assumed in a theoretical analysis of the data obtained from refraction seismic tests, there is a remarkable similarity between the field curves obtained and the theoretical curve as it appears in figure 3. This is illustrated by the time-distance curve shown in figure 4 which was prepared from the field data shown in figure 1, supplemented by two additional shots placed at greater distances from the detectors. The data for this graph were obtained in New England where a relatively thin layer of loose soil was underlain by glacial till resting upon solid rock.

Theory of Earth-Resistivity Method

Experience has demonstrated that many of the materials making up the earth's crust can be identified, in some degree at least, by their reaction to the flow of a direct current of electricity. This is an action of electrolytic nature in which the moisture in the soils and rocks, together with the dissolved impurities, gives to the several materials characteristic resistances to a current flow.[5] These characteristic resistances or resistivities may be used for locating and, to some degree, identifying subsurface formations. Figure 5 illustrates diagramatically the earth-resistivity test and the Wenner electrode configuration (*1*) used by most investigators. In this test a prediction of the character of the subsurface materials is attempted by measurements indicating the magnitude of the resistance to direct current flow. Ordinary moist soils containing moderate amounts of clay or silt, with some electrolytic agent more or less active, have a comparatively low resistance. In contrast, sand, gravel, extremely dry, loose soils, and solid rock usually have relatively high resistivity values. These classifications are too general to be useful, however, and it is very necessary to calibrate the instrument with tests made over local materials which can be identified by exposed faces, test pits, core-drill records, or other means. Curves obtained later for unknown conditions may then be compared with those for known conditions, and a prediction can be made as to the materials lying below the surface.

[5] For a detailed description of the apparatus and a more comprehensive discussion of the earth-resistivity method of test see references (*1, 3, 7, 15, 25, 26*).

Explanation of operation

Referring to figure 5, an electric current is passed through the ground from a direct current supply, usually one or more radio C-batteries, using the two outside electrodes C_1 and C_2. Measurement is then made of the drop in potential between two intermediate points P_1 and P_2, symmetrically spaced at the third points between the current electrodes. The current flow is determined with the milliammeter and the voltage or potential drop with the potentiometer, from which the resistivity of the material is computed by use of the formula

$$\rho = 2\pi A \frac{E}{I}$$

in which

A is the electrode spacing, in centimeters.
E is the drop in potential, in volts.
I is the current, in amperes, flowing in the circuit.

There is an empirical relation such that the "effective" current flows within a depth below the surface equal to A. That is to say, if A equals 10 feet, the resistivity obtained with the formula represents an average of all material existing within 10 feet of the surface. Thus, as the electrode spacings of the system are expanded, the current flow lines encounter the deeper portions of the underlying forma-

tions, such as the rock formation in figure 5. This material, having an appreciably higher resistivity than the overlying soil, affects the average resistivity values, the effect of the lower bed increasing progressively as the test is carried to greater depths.

When using the empirical method of interpretation proposed by Gish and Rooney (*2*) the apparent resistivity ρ_a, obtained by inserting the measured values of A, E, and I from the field tests in the formula for resistivity as given above, is plotted as the ordinate against the electrode spacing A as the abscissa. The inflections in the resulting curve are interpreted as indicating changes in the materials underlying the surface. Where clay overlays rock a curve similar to that shown in the lower right-hand portion of figure 5 is usually obtained. The depth of the surface soil is taken as the value of A (electrode spacing) at which the upward inflection of the resistivity curve occurs. This empirical solution has been used in analyzing data from many tests in the past. Cases were found, however, where the plotted curve was smoothly rounded, with no inflection point, affording no criterion for predicting the depth of the surface material. Another empirical method of analysis has been proposed (*25*) for interpreting such curves, a brief summary of which follows.

Empirical analysis

In figure 6 the smoothly rounded Gish-Rooney or individual-test-value curve is shown as a broken-line curve determined by the plotted crosses. The same field data are shown below this curve in the form of a cumulative resistivity curve determined by the plotted circles. When the values of apparent resistivity are plotted as a cumulative curve, a straight line or a curved line of gentle curvature is usually obtained so long as the "effective" current flow remains within the surface layer. When the electrode spacing is expanded to include increasing amounts of the deeper-lying rock formation the cumulative curve shows an increased curvature upward, reflecting the influence of the higher resistivity of the rock formation. It has been found that straight lines drawn through as many points as practicable on the cumulative curve, and intersecting in the region of increased curvature, will give a good approximation of the thickness of the surface material if the point of intersection of the straight lines is projected to the horizontal or dimensional axis. This is a purely empirical relation with no theoretical basis whatsoever. It has given rather close approximations of the depth of the surface layer in simple two-layer formations, however.

Referring to figure 6, it will be seen that the relatively shallow depth of 14 feet to rock, as determined by the test pit, affects strongly the measured values of apparent resistivity beyond an electrode spacing of about 10 feet. For this reason the plotted values of cumulative resistivity continue to show a rather marked degree of curvature well beyond what might be termed the critical point in the curve. The trend of the Gish-Rooney curve is used to determine the approximate critical point, which in this curve appears to be at an electrode spacing of 10–12 feet. Guided by the indications of the Gish-Rooney curve and such other correlating data as may be available from test pits or borings in the general area, the additional tangent intersections beyond the critical point may or may not be disregarded.

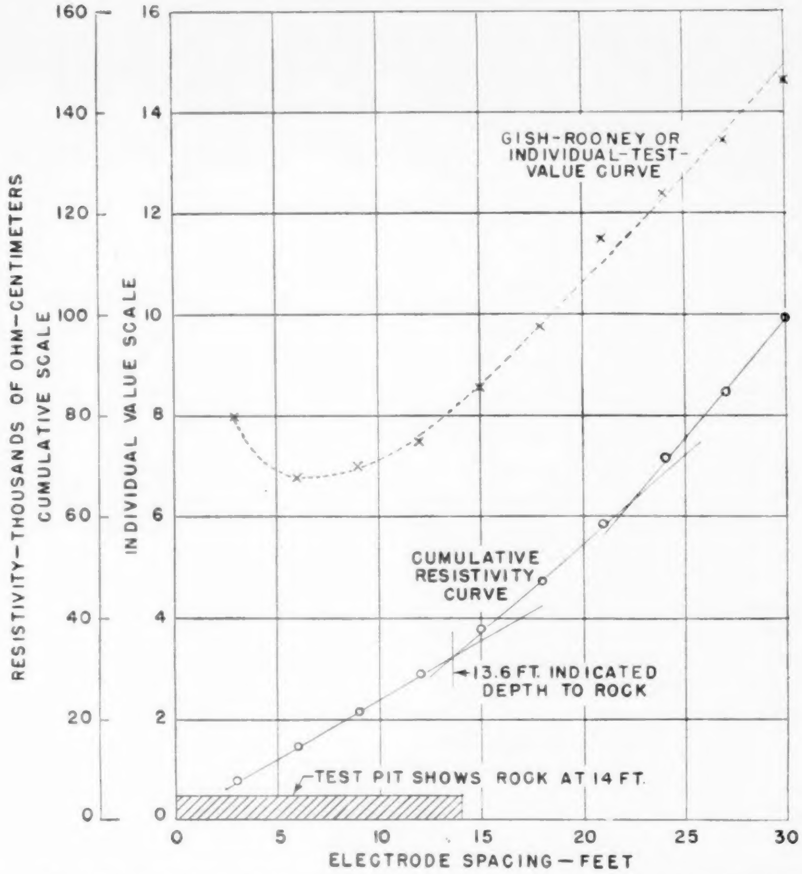


Figure 6.—Typical resistivity data, and analysis by use of the cumulative resistivity curve.

Other methods of analysis of earth-resistivity data based upon theoretical studies have been presented by Tagg (*7*), Hummel (*4*), Roman (*6*, *22*), Wetzel and McMurry (*20*), and others. Sets of theoretical curves for various assumed resistivities and thicknesses of the materials involved have been prepared for use by the operator as control in interpreting the field curves obtained. In some instances the field data are plotted to the same scale as that used in the theoretical curves, and on identical sheets, and are superimposed upon the theoretical curves. Where a fit is obtained by superimposition, the depths of the layers involved, as well as the resistivities of each layer, are obtained. Attempts to use these methods in analyzing the data obtained in the relatively shallow work done by the

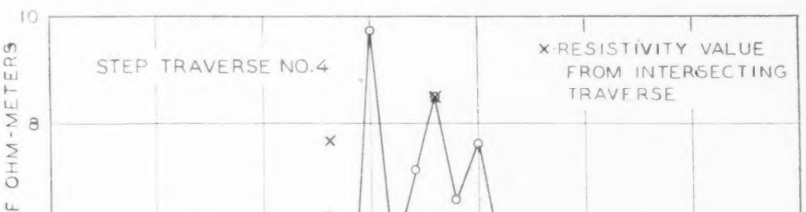


Figure 7.—Step traverse over a deposit of sandy gravel (electrode spacing, 20 feet).

Bureau of Public Roads have been discouraging, due to the time required for such studies and the frequency with which the field conditions failed to conform to those assumed in developing the theoretical curves. The empirical solutions heretofore described have been found to be more practical from the standpoint of time and cost in connection with a given exploration. This might be, in some cases, a deciding consideration between the geophysical tests and the direct methods of exploration ordinarily used.

Traverse surveys

When making surveys of areas, a somewhat different test procedure, one which might be termed the resistivity traverse or constant-depth traverse, is often used. In this, a succession of tests using a fixed electrode spacing is made along the selected traverse line, the interval between test sites being equal to the electrode spacing. The measured resistivity values are then plotted as ordinates against traverse distances as abscissas, and the resulting graph shows the variation in resistivity along the traverse line for a depth equal to the electrode spacing chosen. A typical example is shown in figure 7, the rise in resistivity between the 100- and 500-foot points on the traverse distance scale indicating the presence of higher resistance material within the depth explored. Traverse lines of this type, carried out systematically over an area, permit the preparation of a resistivity contour map such as that shown in figure 8. Such a map may be of considerable aid in rapidly locating and delineating critical areas that require more detailed study, or in locating valuable isolated deposits of granular materials or rock in areas where such materials are scarce.

Rapid Subsurface Exploration Method Needed

Development during recent years of earth-moving equipment of ever-increasing capacity has made possible the quick and economical removal of huge quantities of excavation materials. Operating costs of such equipment are high, however, and a reasonably certain knowledge that the equipment selected will be able to handle all or a major portion of the materials on a given grading job, without costly delays from unforeseen adverse conditions, can be extremely helpful to contractors in establishing reasonable unit bid prices. A thorough investigation of the subsurface formation prior to design of slopes in cut sections will help to avoid the confusion that results when solid rock cuts, anticipated according to the plans, actually are found to be soil or other easily removable materials (or vice versa). Such errors in the classification of materials may lead to costly extra work or changes in design.

Stony soil, talus materials, and thin but continuous stringers of quartz or other hard materials extending throughout a cut may present insurmountable difficulties when attempting to explore subsurface conditions with hand- or power-operated auger equipment. Such troublesome conditions may result in misleading data when the auger is used but will not affect the data obtained with geophysical tests to any appreciable extent. For this reason, preliminary surveys by geophysical methods can be used to considerable advantage in determining the over-all character of the materials to be excavated. Complete and dependable information will make unnecessary hurried changes of alinement and grades to care for increased or decreased quantities of excavation materials, with possible delays of construction operations.

Application of Tests to Highway Problems

It has been found that both seismic and resistivity methods of test are practical for use in the study of many highway construction problems. The earth-resistivity apparatus, by reason of its simplicity of operation and the rapidity with which the shallow tests can be made, is believed to have a more universal application than does the seismograph. Accordingly, when making a detailed geophysical survey of a grading project, it has been the

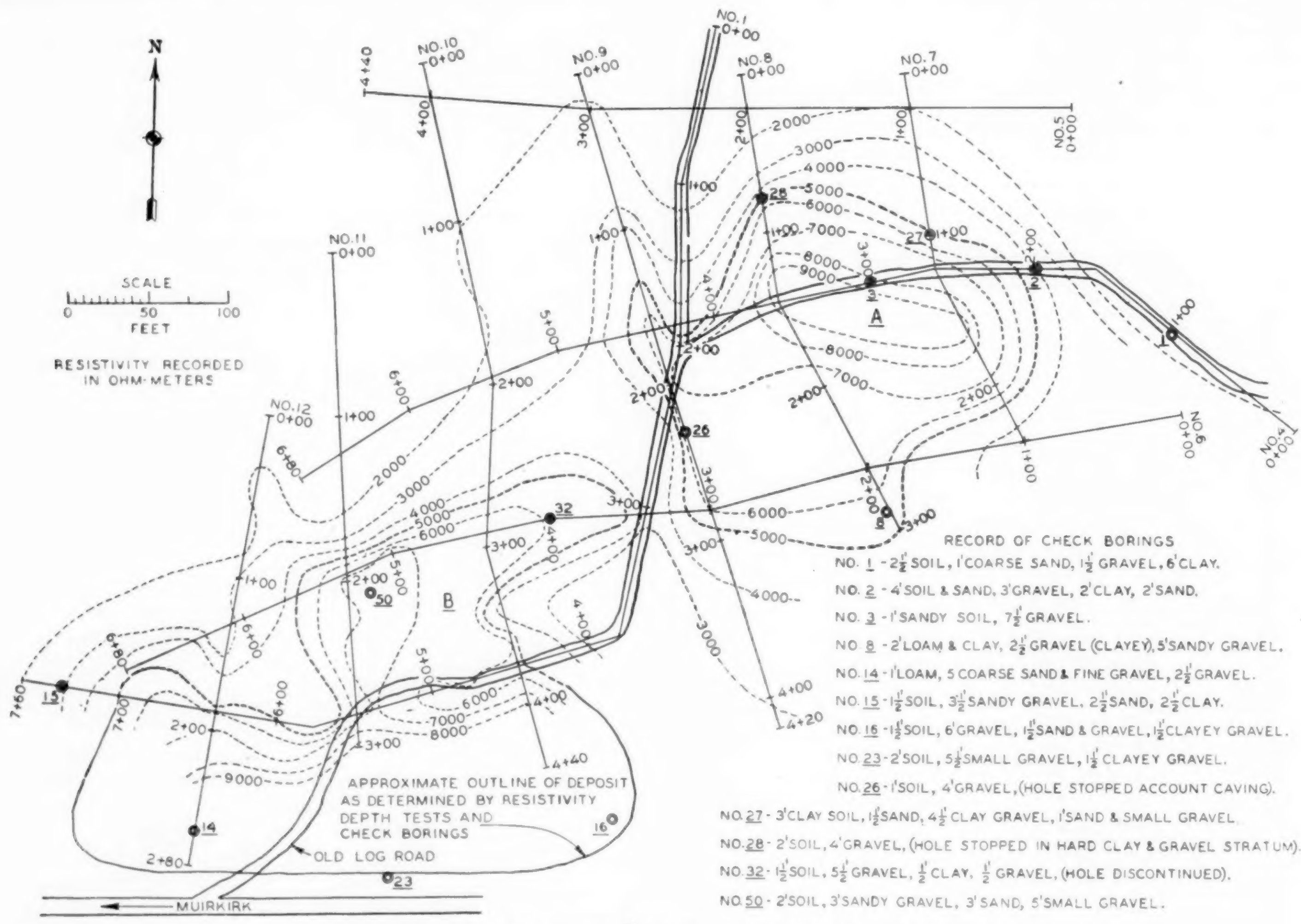


Figure 8.—Resistivity contour map over a deposit of sandy gravel.

Figure 9.—Tightly cemented boulder formation predicted by seismic tests at Pemigewasset River crossing near Lincoln, N. H.

practice of the Bureau of Public Roads to make a resistivity survey first and, if necessary, to follow with a limited number of check tests with the seismograph in areas where the resistivity data fail to identify the subsurface formations adequately. This procedure has proved to be very satisfactory in field investigations of 10 construction projects ranging from 1½ to 12 miles in length, located in Arkansas, Georgia, Missouri, North Carolina, Tennessee, Virginia, and the District of Columbia. Reports have been received on four of these projects which have since been constructed, and the conditions found during construction were substantially as predicted from results of the geophysical tests.

Results of Seismic Tests

In seismic tests, the velocity of the transmitted sound waves generally increases with an increase in the density of the transmission medium. Wave velocities in loose, unconsolidated soil layers range from 600 to 1,500 feet per second. Velocities in more compact subsurface layers range from 2,000 to 9,000 feet per second, the lower ranges of 2,000 to 3,500 usually being associated with clay materials and the higher ranges of 4,000 to 9,000 with compact gravels, badly broken or weathered rock, and soil-boulder mixtures. Solid rock usually allows wave transmission velocities between 10,000 and 20,000 feet per second, depending upon the type of rock and its degree of weathering or fracture. In predicting the character of material that may be found, particularly in the intermediate velocity group (4,000 to 9,000 feet per second), considerable judgment, as well as some knowledge of local geologic conditions, is required. Calibration tests over known subsurface formations are essential for a successful interpretation of the data obtained.

Actual identification of the materials involved is not always necessary, however. For example, broken rock or badly seamed rock, highly compacted shale, or cemented gravel, having similar velocity characteristics, may be expected to offer somewhat similar difficulties in excavation operations, possibly requiring some blasting and special handling and distribution. These same materials will probably show similar load-carrying capacities when considered for foundation purposes, particularly where surrounded by materials which have been left in an undisturbed state.

Use at bridge sites

As an example, seismic tests made in New Hampshire at a proposed bridge site on the Pemigewasset River, near Lincoln, showed a comparatively high wave velocity for material lying only a few feet below the surface and apparently continuing to a depth of at least 40 feet. This material, with a wave velocity of 9,400 to 9,600 feet per second, was predicted to be a tightly cemented boulder formation with excellent load-carrying capacity. Figure 9 shows the excavation subsequently made for one of the bridge piers at this location. The material was so tightly cemented together that only a simple sandbag cofferdam was required. Soundings and drill holes through material of this type would be impossible or could be made only with great difficulty and at considerable cost.

Another bridge location, near Crater Lake in Oregon, was investigated by the seismic method in about 3 hours. The data obtained showed the subsurface formation to be a very dense material providing a wave velocity of 8,400 to 8,600 feet per second. Here, again, there could be no doubt regarding the existence of adequate foundation materials. Figure 10 shows the seismic data for two of the three tests made at this location.

Data for slope design

Experience is needed to determine the particular slope design that will be adequate where certain materials within a local area are involved. With proper calibration data, the seismic method often can be relied upon to establish definitely the presence of these materials. As an example, the data in figure 11 show the presence of and depth to the predominant material, shale.

As mentioned previously, portability of equipment is of primary importance to the successful application of geophysical methods of test in preliminary surveys for a highway location. Figure 12 shows typical terrain encountered in the construction of roads in National parks and forests in various parts of the country. In designing a modern highway through such country, any information regarding the materials likely to be encountered in excavating cut sections is important. A close

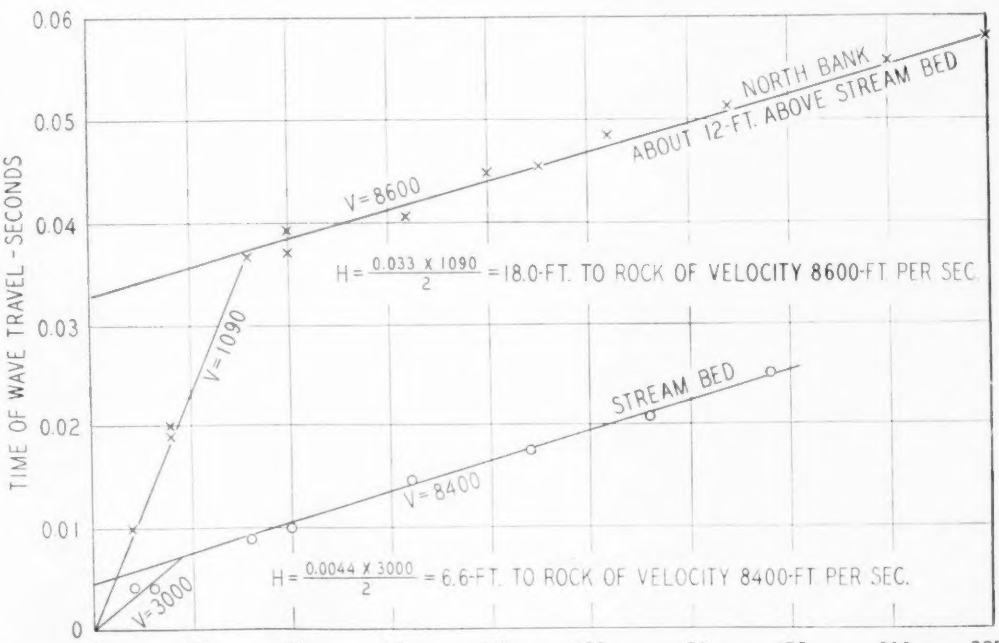


Figure 10.—Time-distance graph from two seismic tests at a bridge site near Crater Lake, Oreg.

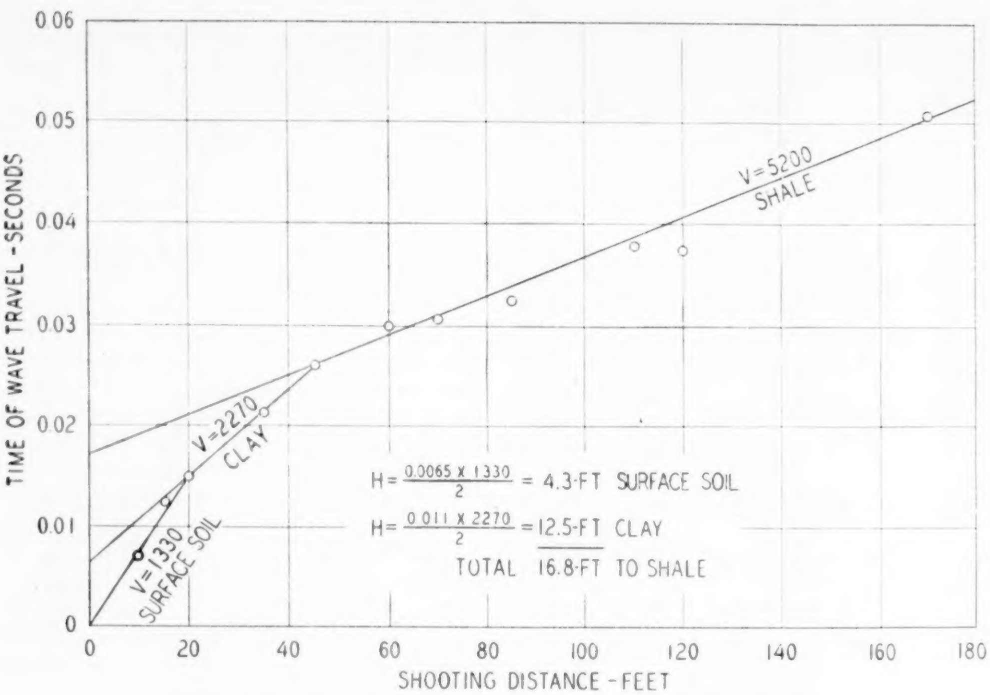


Figure 11.—Refraction seismic test over a shale formation.

balance of quantities must be maintained both in the interests of economy and to avoid waste or borrow areas which would mar the natural scenic beauty of the roadside. Therefore, a design prepared for solid rock, with a ½ to 1 slope in cut section (such as the one shown in figure 12), could lead to embarrassing difficulties should a comparatively loose earth or talus material be encountered, requiring a 1½ to 1 slope reaching high up the mountainside. Large quantities of material would have to be wasted or cared for by substantial changes in alinement and grade. Conversely, where earth slopes are expected and rock is found, a source of borrow would be required for adjacent large fills unless major grade changes were made.

The ridge from which the photograph shown in figure 12 was taken originally had been assumed to contain solid rock. A tunnel several hundred feet in length was proposed to carry the roadway through the ridge, some 100 feet below the top. Test pits dug to obtain design data for portal construction failed to encounter rock above grade. Several weeks were required for this exploration work, which cost hundreds of dollars, and finally a redesign for an open cut was found necessary. Seismic tests requiring no more than 2 or 3 hours were sufficient to establish the fact that no solid rock existed in the hill. The excavation during construction was made with the usual heavy earth-moving equipment. Studies made with seismic equipment at other sites have been of value in portal design and in indicating the probable need for tunnel lining.

Slide conditions

Another problem to which refraction seismic equipment has been applied occurs in regions where slide conditions are prevalent. In some cases the loose talus material frequently involved in a slide rests upon a sloping shale formation which constitutes the sliding surface. This talus material has velocity characteristics differing from those of the more compact shales, making possible the location of the plane of separation.

Although the refraction seismic test has proved of value in preliminary surveys in various phases of highway construction, as has been pointed out, it has not been used to the same extent as the earth-resistivity test in recent years because of the greater time required for a seismic test. Six or eight seismic tests per 8-hour day is about the maximum number to be expected, under reasonable field conditions. Fifteen to twenty resistivity tests are usually possible under similar field conditions. Seismic tests can be utilized as a completely independent check of the indications of the more rapid resistivity tests, however, and are used for this important purpose in the routine work done by the Bureau of Public Roads.

Figure 12.—Rugged terrain in a National forest where portable equipment for subsurface exploration is invaluable.

Results of Earth-Resistivity Tests

In a subsurface survey in the field, it is an established procedure to make calibration tests with the resistivity apparatus over exposures of formations believed to be typical of those in the area of immediate interest. Resistivity curves for the known conditions are then used for comparison with curves obtained over unknown conditions elsewhere in the area. From these comparisons reasonably accurate predictions can be made regarding the materials to be encountered below the surface, and their location. Figure 13 shows typical resistivity curves obtained in Arkansas, in the Ozark National Forest, in the course of a resistivity survey of about 22 miles of proposed roadway. The calibration curves on the left were obtained for heavy sandstone ledges interbedded with shales and for the soils and decomposed shales typical of the region. These latter are materials that could be handled with the heavy self-loading scraper. The curves of the right-hand graph are examples of the field curves obtained in the survey along the right-of-way of the proposed roadway. Little difficulty was experienced in predicting the types of materials involved for the several curves shown. Figure 14 shows the two general types of material over which calibration tests were made.

Based upon the usual methods of direct exploration, the original slope design called for rock slopes over a considerable portion of the right-of-way. Actually, earth materials, as predicted from the results of the resistivity survey, were found in a majority of the cuts during the construction of about 14 miles of roadway thus far completed. The entire 22 miles was investigated in about 12 working days, one 8-mile section being covered in 3½ days.

In northwest Georgia, resistivity calibration tests over solid rock and over earth formations produced curves as shown in the left and in the lower right-hand graphs, respectively, of figure 15. Although the shapes of the curves obtained are quite different from those obtained for materials of the same general classification in Arkansas, the two materials, rock and earth, can very easily be distinguished one from the other. On the basis of these calibration data, the typical field curves shown in the upper right-hand corner were all interpreted as identifying earth materials easily removed by self-loading scrapers. Figure 16 shows the two types of material over which calibrations were made.

In the Great Smoky Mountains National Park in western North Carolina, the dense granite rock formations typical of that area weather into a highly micaceous decomposed rock material that can be removed with scraper units. As shown by the calibration curves in figure 17 (solid-line curves), this material has an extremely high resistivity, 1.5 million ohm-centimeters, which is ten times as great as resistivities found in some solid rock in other parts of the country. Due to the fact that the parent rock in a solid, unweathered state has even higher resistivities (4 to 5 million ohm-centimeters), it is again possible to differentiate between earth and rock excavation. The appearance of the materials over which the calibrations were obtained is shown in figure 18. That section of the Blue Ridge Parkway on which the resistivity survey was made has not yet been built and no confirming correlations are available at the present time.

In southeast Missouri, the porphyry rock found in the vicinity of Farmington has a resistivity as indicated by the upper curve of figure 19, while a calibration test over the soil common in the same area produced the lower curve of the figure, indicating almost no resistance to direct current flow. No difficulty was encountered in determining the type of material present in all but one cut of all those investigated on a 4-mile section.

Other resistivity surveys on construction projects in Maryland, Tennessee, Virginia, and the District of Columbia provided information regarding the subsurface formations that agreed closely with conditions actually found during construction.

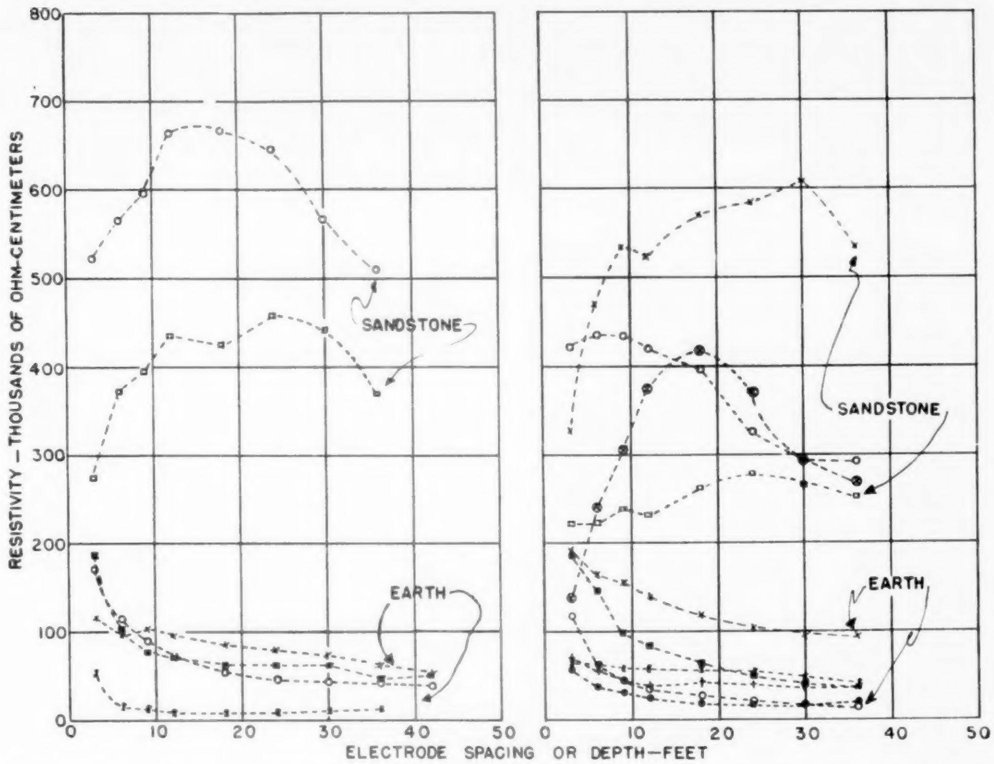


Figure 13.—Resistivity calibration curves (left) and typical field curves (right) obtained in the Ozark National Forest in Arkansas.

Figure 14.—Locations where resistivity calibration curves shown in figure 13 were obtained over rock (upper) and earth (lower).

Application to foundation problems

Earth-resistivity tests can be of assistance also in a subsurface study of the foundation conditions existing at proposed building sites, bridge locations, and in other areas where solid rock foundations are required or desirable.

In 1942, at the request of the Navy Department, a resistivity survey was made of a 150-acre tract at Carderock, Maryland. The site is underlain with rock and information was desired as to the depth to rock throughout the reservation. Altogether, over 500 depth tests and upwards of 10½ miles of constant-depth resistivity traverse were made in carrying out the survey. From the information obtained a rock contour map (fig. 20) was drawn up showing probable rock elevations on 2-foot contours over the entire area. An accuracy of ±2 feet at any point in the area mapped was predicted. In 1944 an existing building with a width of 120 feet was extended for 1,800 feet in the area that had been mapped. Cross sections of the rock surface as found, obtained at intervals of 10 feet along the building axis, showed a difference in total amount of stripping of less than 6 percent from that computed from the rock contour map prepared in 1942. About 100,000 cubic yards of stripping were involved.

Figure 21, showing typical traverse data obtained in this study, illustrates how the resistivity test can be used in a preliminary survey to obtain information that may be used to guide a detailed survey by borings and eliminate many unnecessary soundings or borings. The flat-lying portion of the curve suggests a uniform condition for much of the distance traversed. The peaks in resistivity indicate those areas where direct borings

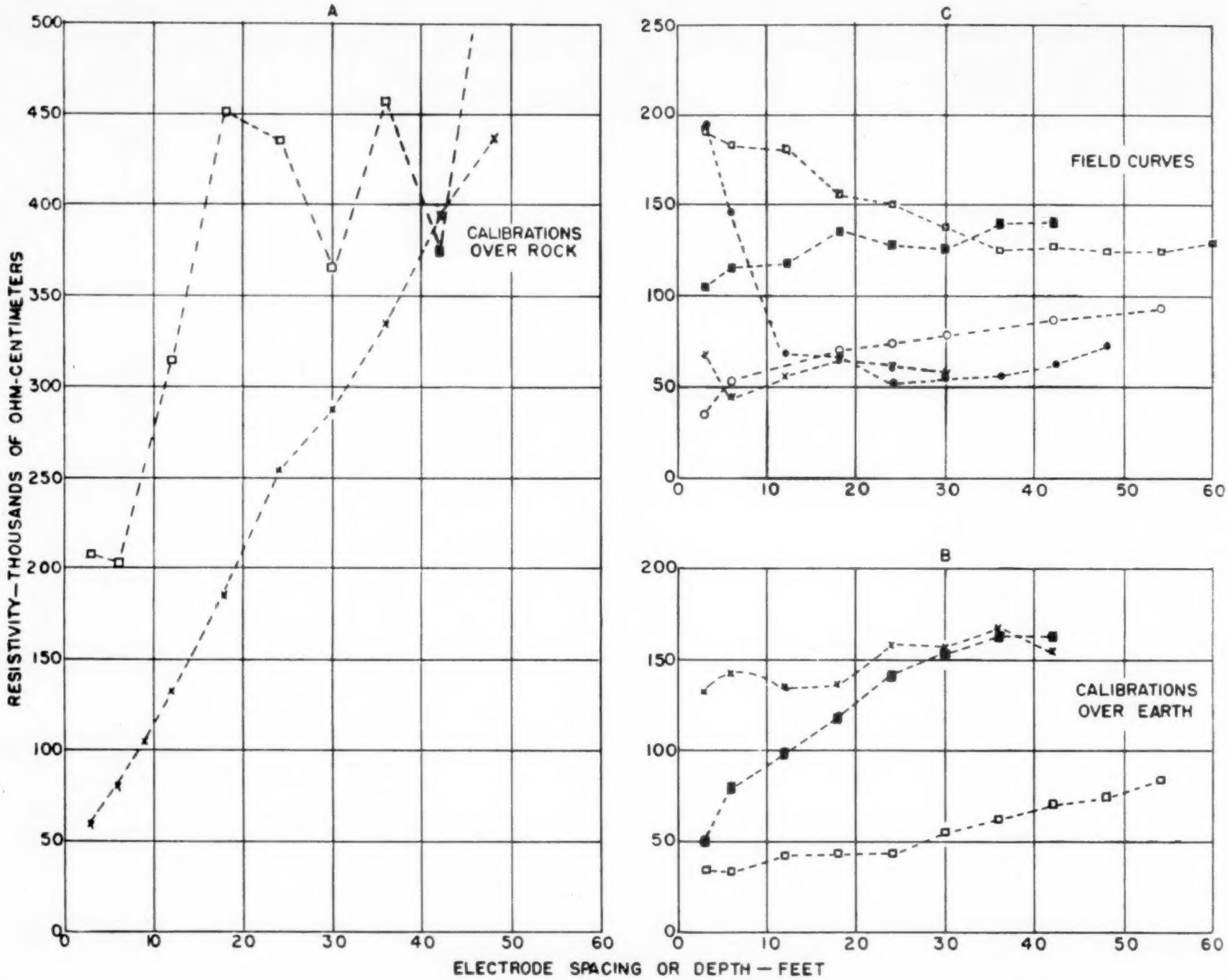


Figure 15.—Resistivity calibration curves and typical field curves obtained in northwest Georgia.

should be concentrated to delineate in detail the obvious anomaly. These buried ridges of rock can be traced across wide areas, indicating regions where excavation will be difficult or where foundation conditions will be excellent at shallow depth. The underlined dimension figures shown are depths to solid rock obtained by resistivity depth tests made at 100-foot intervals along the line of the traverse. The two depth curves shown in the inset are a striking indication of radical changes in the subsurface at stations 2+00 and 13+00 of the traverse.

In bridge foundation studies there have been numerous instances when the routine subsurface survey, using the usual methods of probing, wash boring, or drilling, has failed to disclose unusual conditions later found during construction. Piers designed originally for solid rock foundations have had to be carried to considerably greater depths than those shown on the original plans, or supported upon piling extending to rock at a lower elevation. Figure 22 shows several resistivity depth curves obtained in a postconstruction survey of a bridge crossing of the Flint

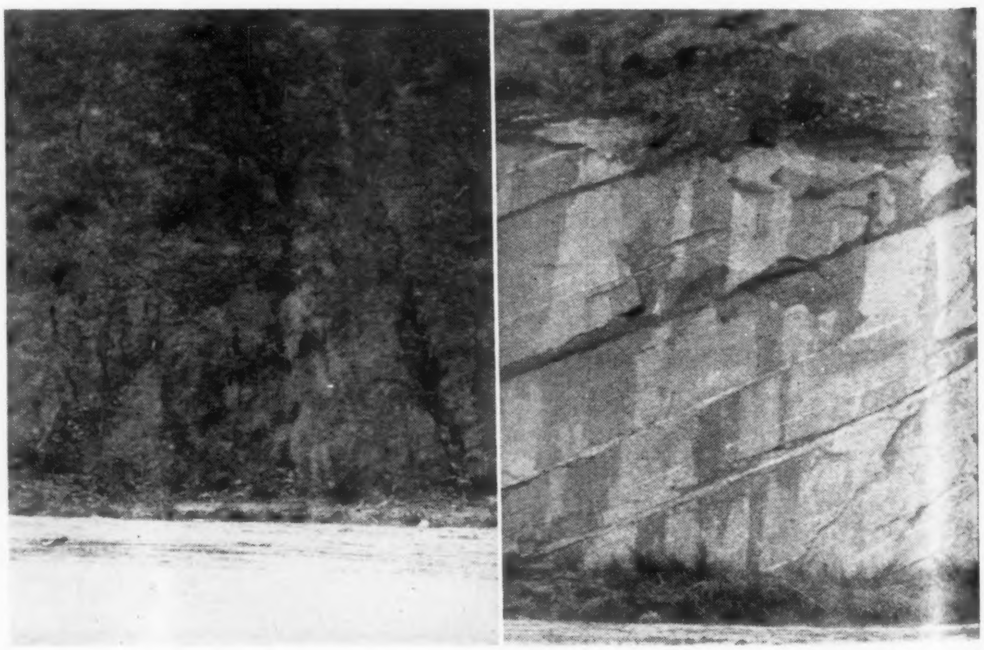


Figure 16.—Locations where resistivity calibration curves shown in figure 15 were obtained over earth (left) and rock (right).

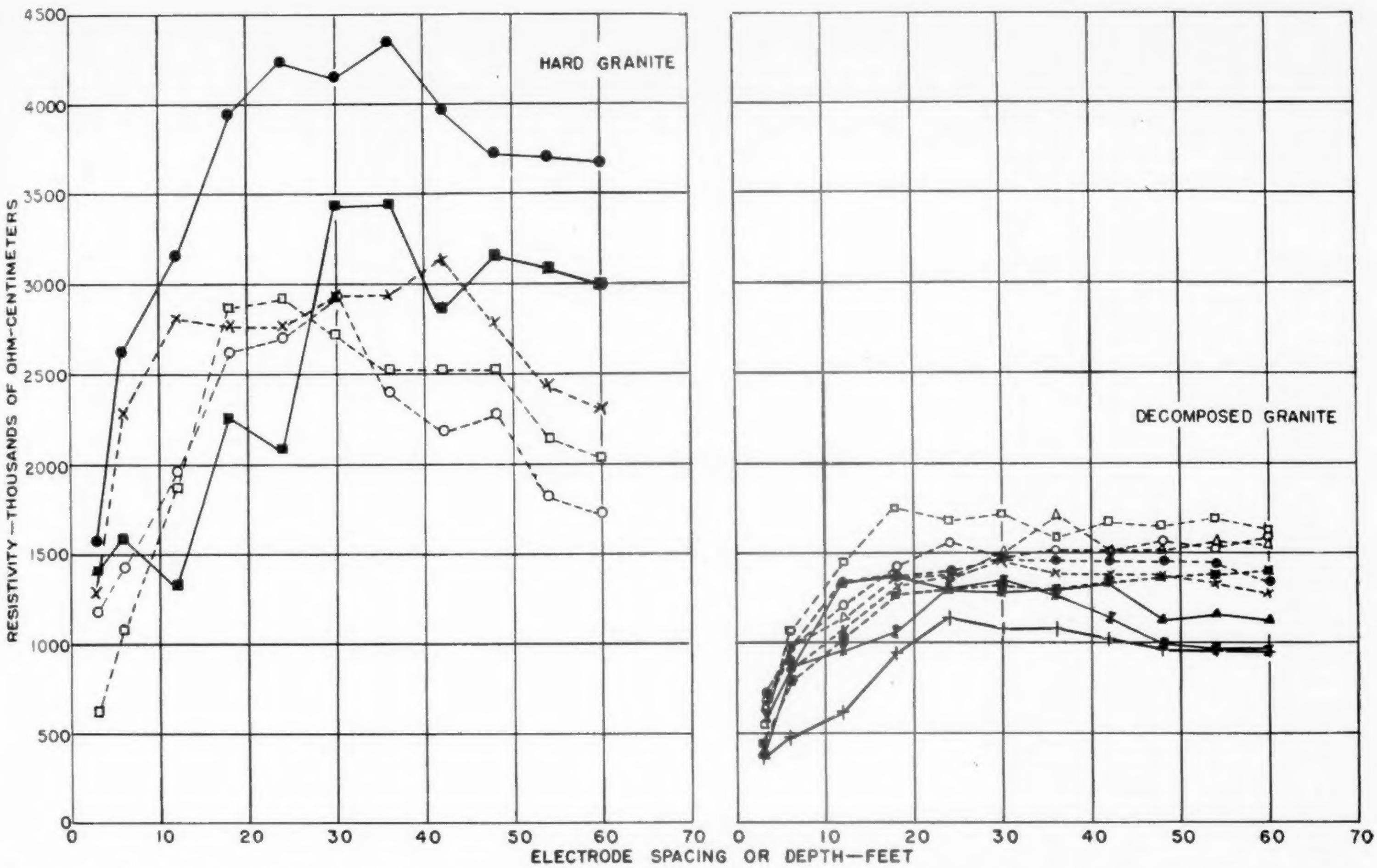


Figure 17.—Resistivity calibration curves (solid lines) and typical field curves (broken lines) obtained over solid and decomposed granite in North Carolina.

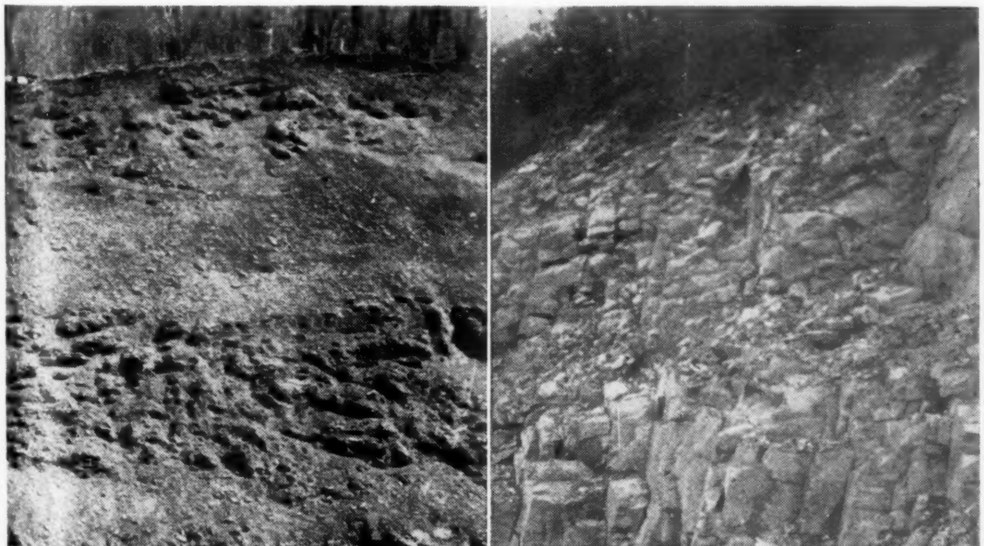


Figure 18.—Locations where resistivity calibration curves shown in figure 17 were obtained over decomposed granite (left) and solid granite (right).

River in southwest Georgia. The individual graphs show the plan data for depth to rock, the depth to rock as found during construction, and the depth to rock as predicted from the resistivity data. The general agreement between the results of the resistivity tests and the actual conditions existing is apparent.

Although it is not possible to make an unqualified statement regarding the effectiveness of the resistivity test generally in all localities and under all possible combinations of geologic formations, the fact remains that 1 or 2 hours' work at a particular location will usually determine the extent of its usefulness in solving the particular problem at hand. The data from the tests made in Georgia are similar to those that have been obtained elsewhere in areas where the river deposits have shown resistivity characteristics differing from that of an underlying rock formation.

Tests in swampy areas

The investigation of swamps, peat bogs, and salt-marsh areas by geophysical tests probably constitutes a marginal application of such methods, since simple probings are often effective in these areas. However, since a resistivity depth test to depths of 60 feet can be made in a period of 12 to 15 minutes, the deeper muck deposits can be studied economically in competition with direct probings. Where sand lenses are likely to be present

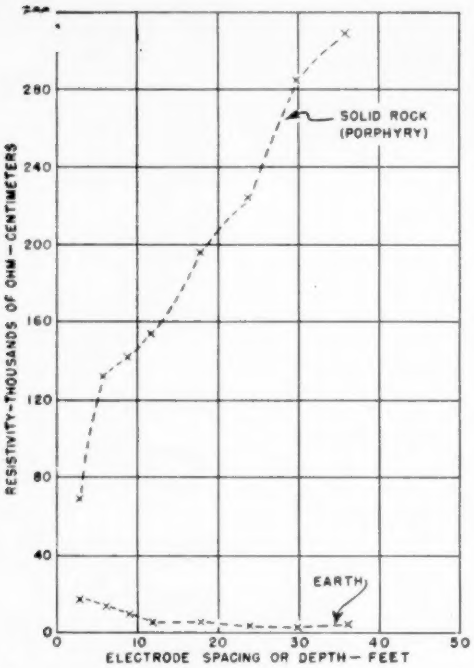


Figure 19.—Typical resistivity calibration curves over solid rock and earth formations in southeastern Missouri.

within a relatively deep layer of muck or peat, probings can result in erroneous information, being stopped by relatively thin sand layers. The resistivity test, due to the large volume of material involved, will not be appreciably affected by thin sand lenses and will indicate depth to a true bottom formation.

The curves shown in figure 23 were obtained in a study of the application of resistivity tests to determine the depth of peat bogs. This study, carried out in Michigan in 1941, confirmed earlier test results obtained in a study of peat formations in Wisconsin as reported by Kurtenacker (*9, 10*) and demonstrated that resistivity tests can be used successfully in determining the depth of peat and muck layers.

Figure 24 shows results of a resistivity survey along a taxiway at the Washington National Airport. The resistivity tests not only indicated the bottom of the floating sand-gravel fill upon which the taxiway was placed, but they also rather effectively located a second horizon comprising the sand and gravel bed of the river. The conditions as they exist were determined by data obtained from the auger holes shown in the figure. The hatched portions of the columns representing the bore holes denote the thickness of the sand-gravel fill, and the solid black portions indicate the thickness of the relatively soft silt on the river bottom.

It is of interest to note the resistivity peaks occurring in the 10-foot depth resistivity traverse, shown in the lower portion of the figure, which coincide with the thicker portions of the granular fill. Even the small difference of a few feet in the over-all depth of the muck from place to place had caused differential settlement sufficient to affect the pavement of the taxiway.

Knowledge of local geology essential

Just as with the seismic test, a working knowledge of the local geology is necessary when attempting to predict the actual character of the materials below the surface from resistivity tests. Figure 25 shows two resistivity traverses, the upper one made over a rock ridge rising almost to the surface, the lower one made over a sand and gravel deposit. The similarity of the two curves might lead to error in predicting the type of material without at least a general knowledge of the local geology. The depth tests shown on the right of figure 25, however, offer some clue as to the actual material involved. When a solid rock formation is present beneath a soil overburden a sharply rising curve is usually obtained, similar to the curve shown in the upper right-hand graph. The dipping curve shown in the lower right-hand graph for the sand and gravel formation suggests to the experienced operator, acquainted with the local geology, that such a formation is likely to be present. Descending curves of this same general type obtained in Arkansas, however, might involve a sandstone ledge underlain by decomposed shales. Or, in southwest Colorado, a curve of this type might be obtained with talus material overlying low-resistivity shales. It is necessary to depend upon a study of local geology and upon calibration tests over exposed materials in the same region when attempting a classification of the materials involved.

In Pennsylvania, a depth test was made at the location of a proposed drill hole in an investigation of foundation conditions for a bridge to carry the Pennsylvania Turnpike across the Susquehanna River. The resistivity depth-test data indicated a definite change at a depth of 27 feet, as shown in figure 26. The consultant geologist suggested that the underlying formation might be shale. The data for this curve were obtained in about an hour's time. In contrast, a drill crew, starting simultaneously with the resistivity test, spent 2½ days in reaching the shale at 26.5 feet.

■ TEST PIT DATA

NO	ROCK ELEV	REMARKS	NO	ROCK ELEV	REMARKS
1	118.4	SUBSURFACE EXPLORATION FOR WIND TUNNEL	11	121.4	SUBSURFACE EXPLORATION FOR MODEL STORAGE BUILDING
2	118.3		12	120.3	
3	117.7		13	120.6	
4	117.4		14	125.5	
5	117.3		15	123.3	
6	122.0		16	123.9	
7	122.7		17	114.2	JUNE 1942 TEST PIT AND 6" AUGER
8	115.9		18	110.0	
9	116.1		19	106.4	
10	113.1		20	117.7	
			21	117.8	MAY 1942
			22	104.6	
			23	118.3	

● CORE DRILL DATA*

NO	ROCK ELEV	REMARKS	NO	ROCK ELEV	REMARKS
1	118.9	HARD ROCK	13	118.4	HARD ROCK
2	121.3	SEAMED ROCK	14	122.7	
3	118.0		15	121.9	
4	122.2		16	120.4	
5	123.1	HARD ROCK	17	119.2	
6	116.9		18	118.7	
7	115.3	BROKEN ROCK	19	119.5	
8	118.7	ROCK	20	120.5	
9	114.7	HARD ROCK	21	121.7	HARD ROCK UNDERLAIN BY SOFT ROCK
10	116.1				
11	121.7				
12	119.1		22	125.3	HARD ROCK

*CORE DRILL DATA OBTAINED PRIOR TO CONSTRUCTION OF BASIN

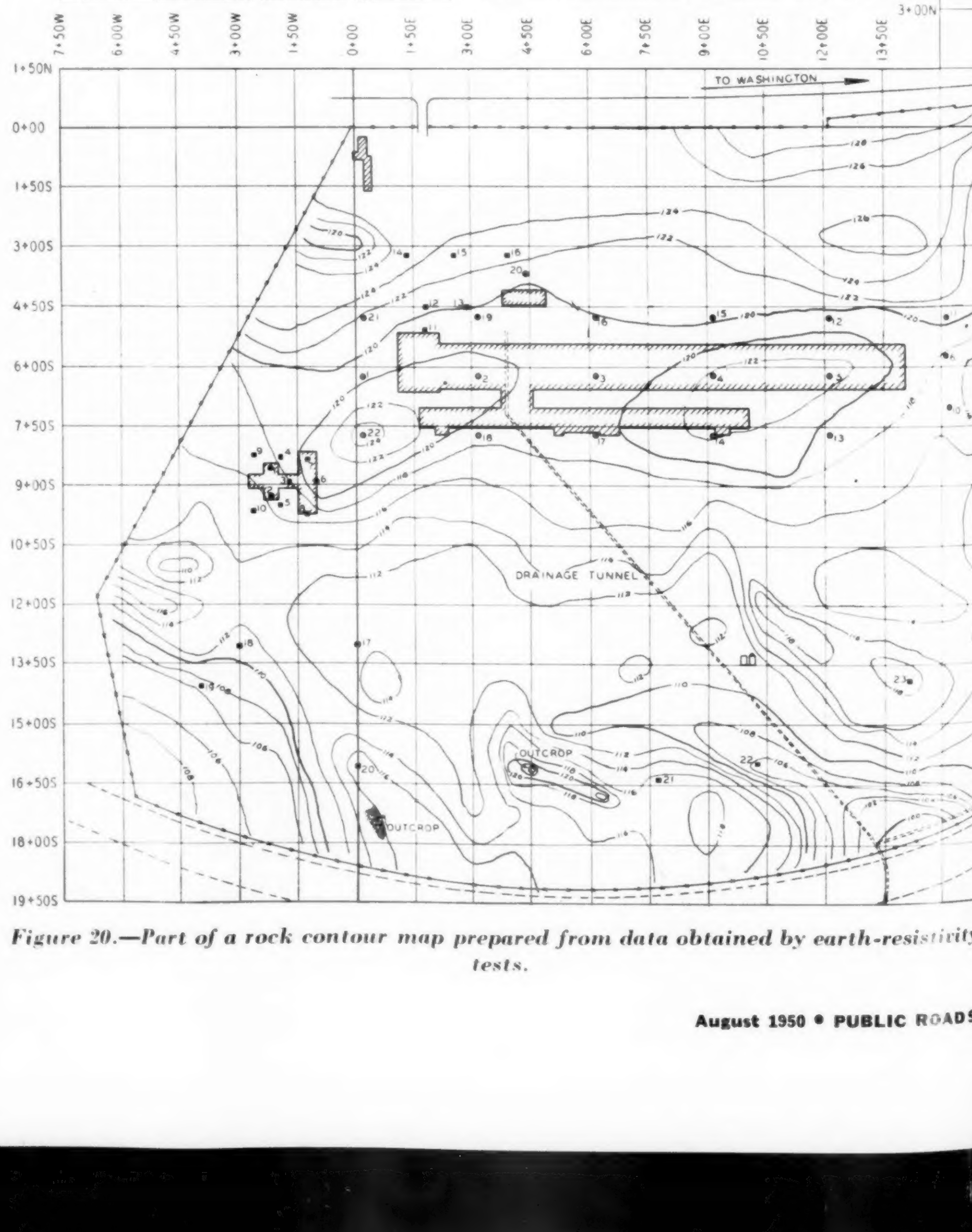


Figure 20.—Part of a rock contour map prepared from data obtained by earth-resistivity tests.

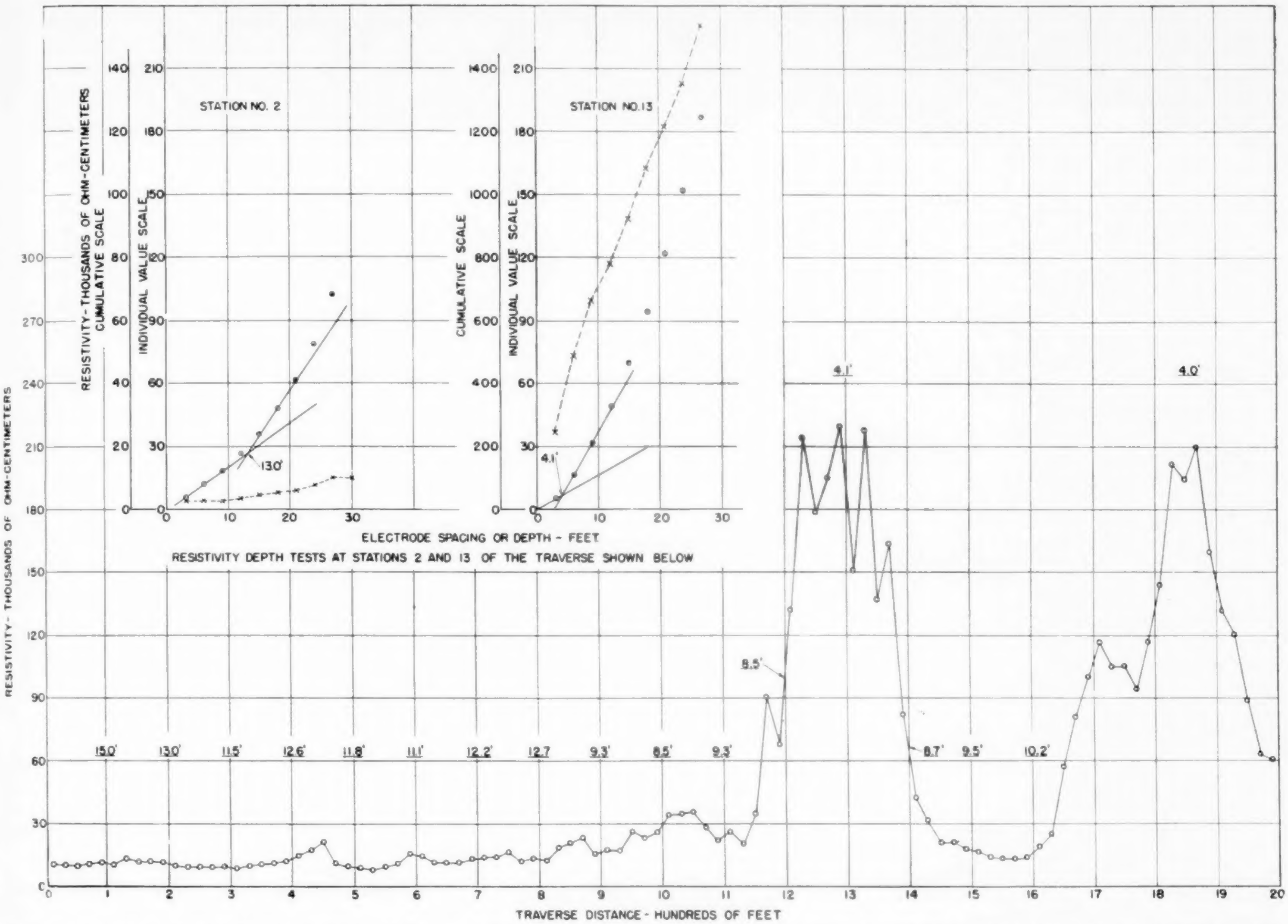


Figure 21.—This earth-resistivity constant-depth traverse discloses abrupt changes in rock surface underlying a clay soil overburden. The traverse involved a 20-foot depth along a 2,000-foot line. The underlined figures show results of resistivity depth tests for depth of overburden; curves for two such tests are shown in inset.

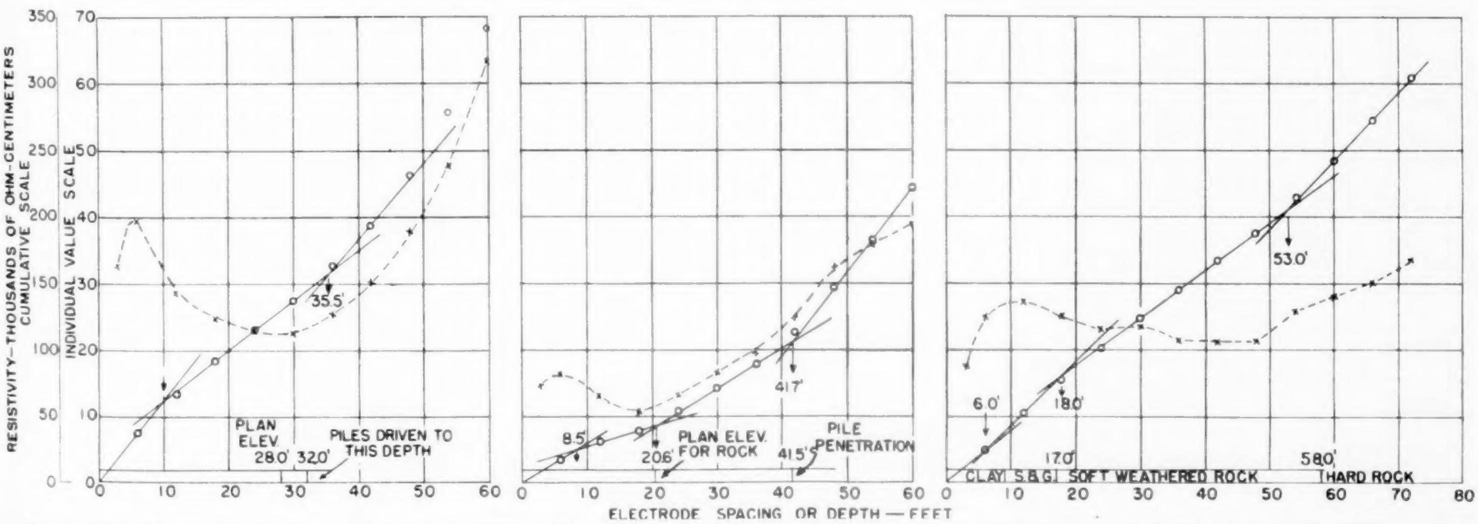


Figure 22.—These earth-resistivity tests at Flint River crossing in Georgia located the subsurface rock for bridge foundations more accurately than drilling.

Advantages and Limitations of the Geophysical Methods of Test

The seismic test is particularly useful for determining the presence or absence of dense, solid rock. The high velocity usually associated with such formations makes the determination quite dependable. Although the resistivity test will, in most instances, indicate the depth of overburden to a high-resistivity formation such as rock, it cannot, in the absence of confirming geologic data, furnish a completely dependable basis for predicting the presence of rock in all cases. As has been shown, sand and gravel under special con-

ditions can have reasonably high resistance and show subsurface anomalies quite similar to those shown by solid rock. However, in areas where solid rock layers are interbedded with less dense materials such as shales, as occurs in Arkansas and in many other areas, the resistivity test is much the better tool since it is possible to detect the change from hard rock to softer, less resistant shales. The seismic test under such geologic conditions would be limited to an indication of the depth of overburden to the high-velocity sandstone or limestone and the lower-velocity shales could not be located. This results from the fact that the first wave to reach the detector will usually cause such high degree of activity in the galvanometer elements controlling the deflections of the photographed light rays as to preclude the possibility of detecting any subsequent wave arrival through the underlying low-velocity formation.

The resistivity test, particularly the resistivity traverse, offers a practical means for the rapid investigation of large areas in search of localized deposits of gravel, sand, or other granular materials useful in road construction. The method can be used also to determine the extent of special soils, such as impervious silty and clayey soils, which might be useful for earth-dam and levee construction.

The seismic test is not well adapted for an area survey, but is best applied to the determination of conditions at a single designated spot or limited area such as a dam site or bridge location. Even in the limited areas, if differential weathering has been in progress,

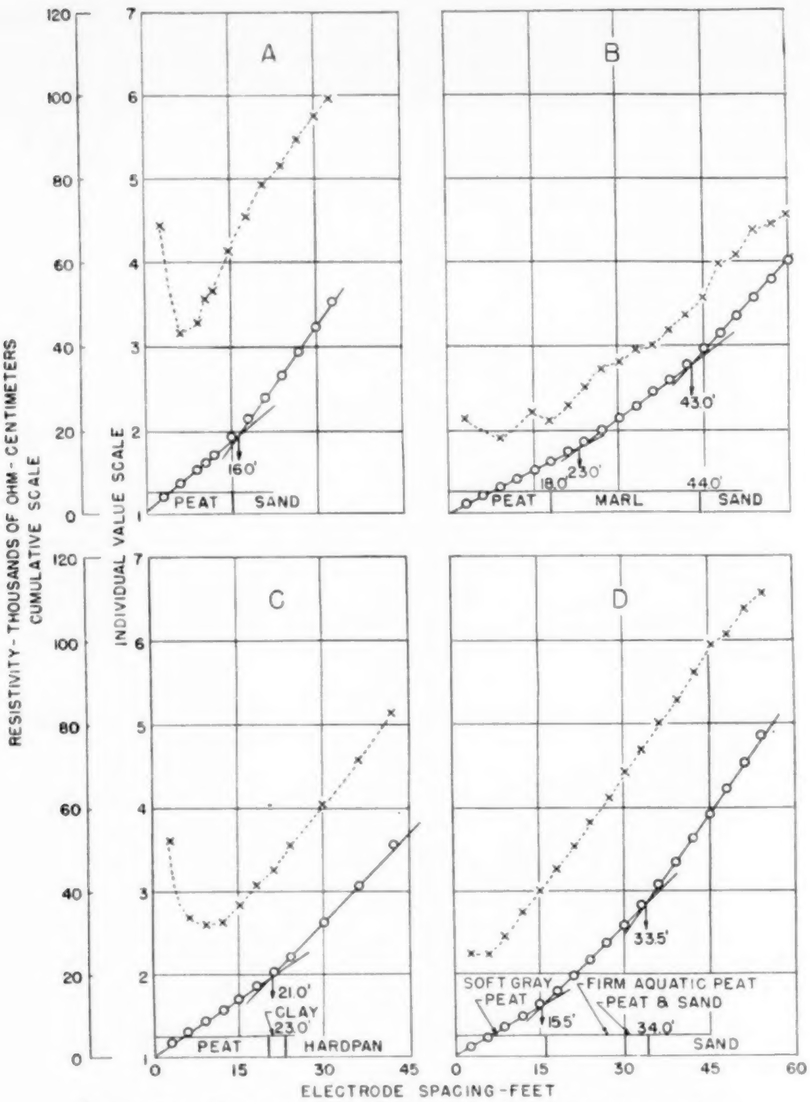
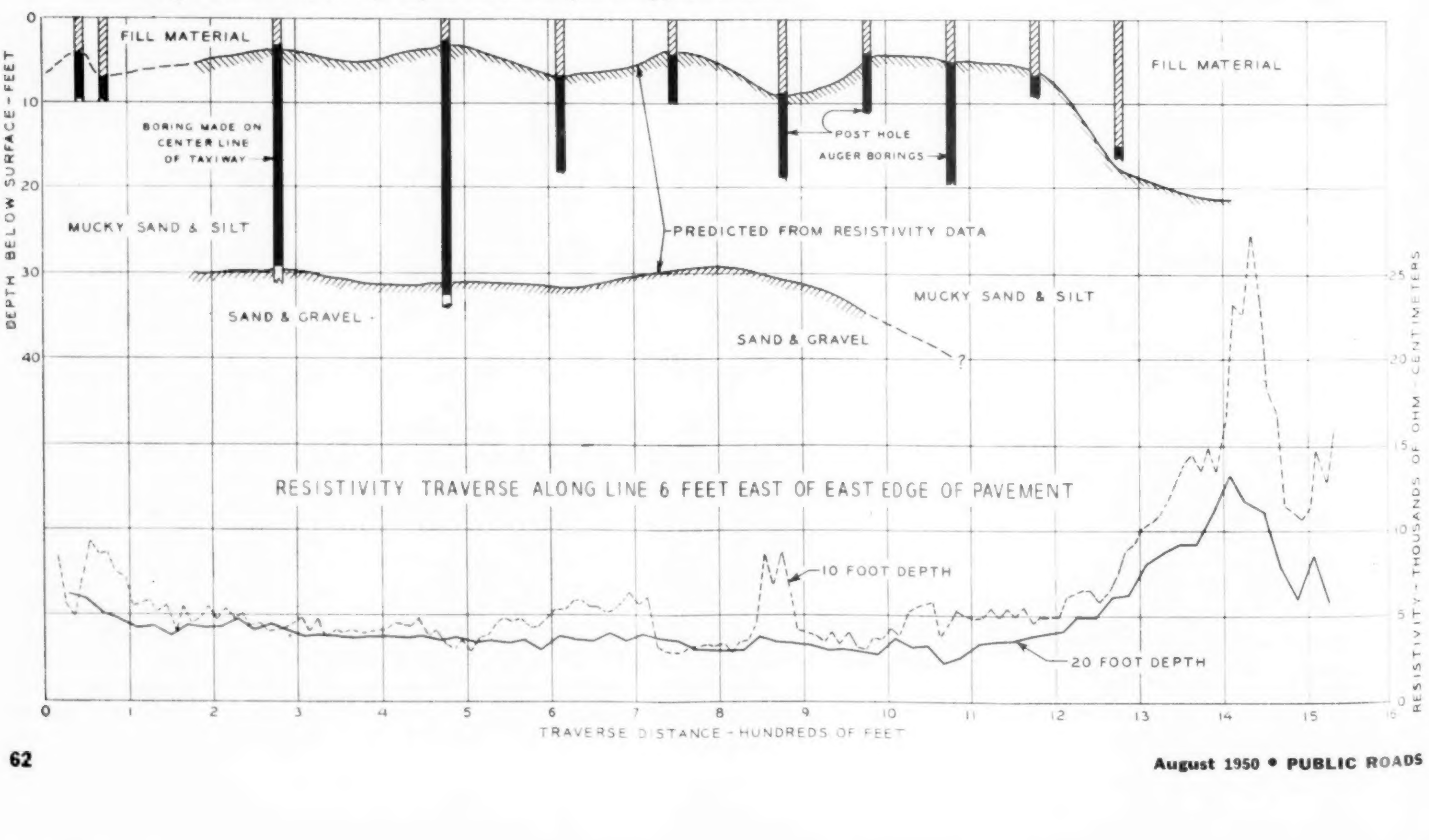


Figure 23.—Resistivity depth tests over peat-bog formations.

Figure 24 (below).—Results of earth-resistivity tests along the edge of a taxiway at the Washington National Airport.



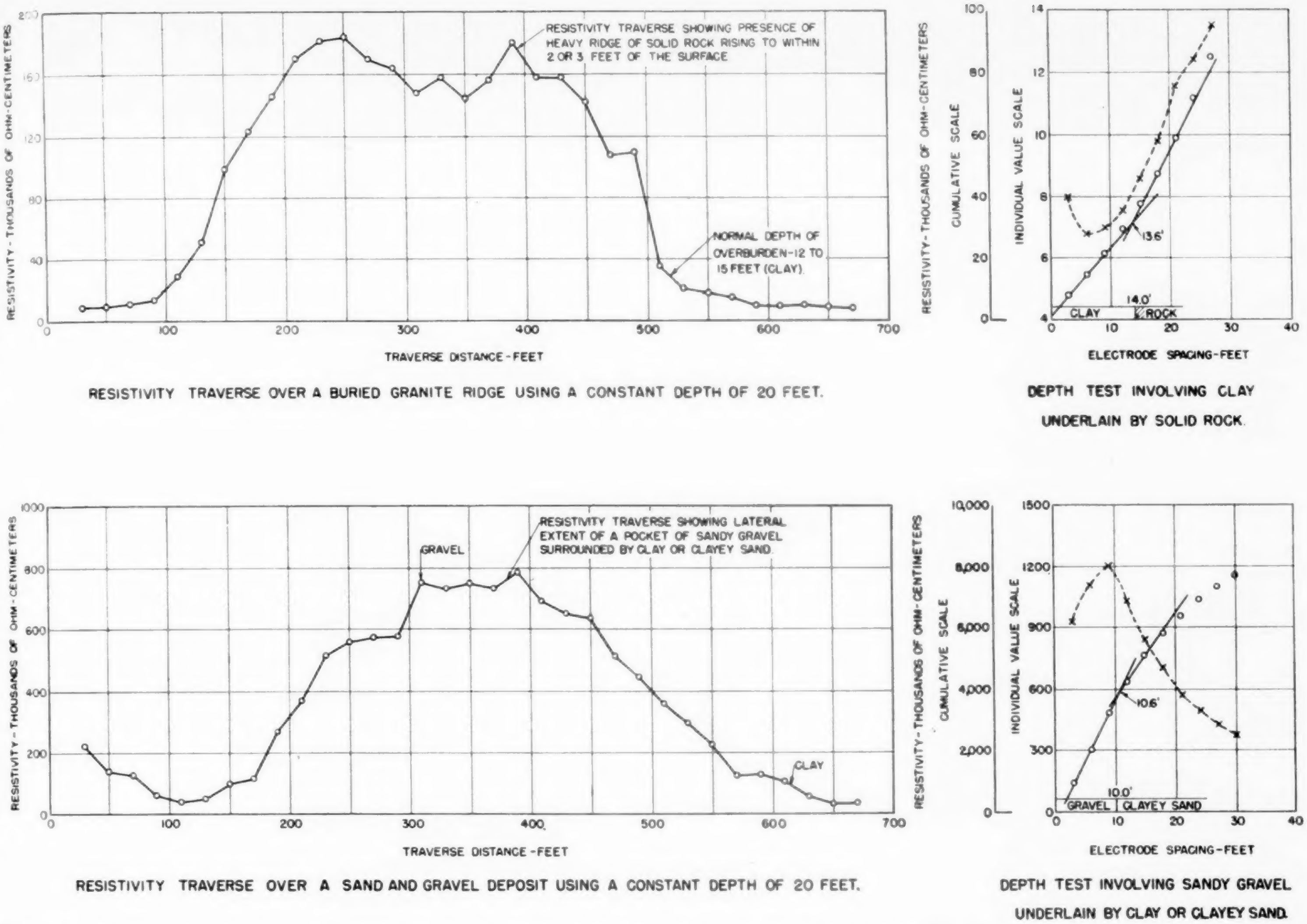


Figure 25.—Resistivity traverses over a rock ridge and a sand and gravel deposit are similar in appearance, but depth tests and a general knowledge of local geology offer some clue as to the actual material involved.

leaving pinnacles and deep valleys in otherwise hard rock (a condition sometimes encountered in limestone formations), the resistivity test may possibly prove the more valuable of the two methods. In such cases the sharp irregularities of the rock surface present unfavorable conditions for consistent interpretation of the seismic data (*24*). To the writer's knowledge, there has been no report on results of resistivity tests carried out in such areas.

The use of explosives as required in the seismic method is not desirable in thickly populated areas. Compliance with local regulations regarding possession and transportation of explosives, sometimes rather strictly enforced, can be troublesome and inconvenient, placing a further handicap upon seismic exploration.

As mentioned previously, the time required for conducting a seismic test can vary from 1 to 3 hours, depending upon local conditions, while resistivity tests can be made at a rate of 3 per hour to depths of 60 feet in rugged mountainous terrain. A seismic party may require one or more men than are necessary for the efficient operation of the resistivity apparatus, particularly in isolated areas

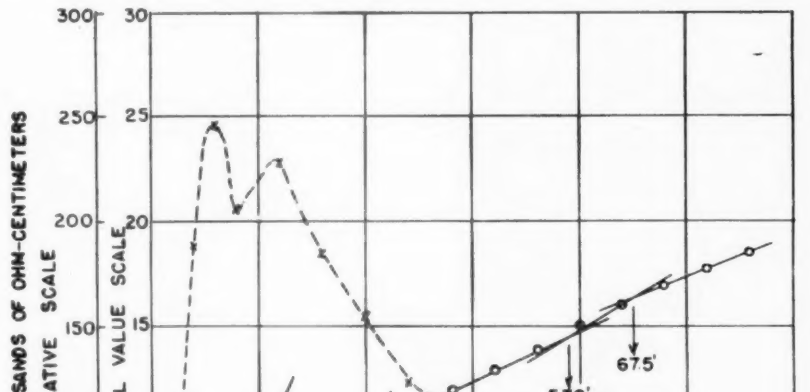


Figure 26.—This resistivity depth test accurately located an underlying shale formation.

where supplies of explosives and film-developing equipment must be carried in by hand. However, stray currents leaving cross-country pipe lines, or emanating from electric railway systems in urban areas, and buried utilities such as water and gas pipes, can be troublesome when making a resistivity survey. These will not affect the efficient use of the seismograph.

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Highway Bridge Location (No. 1486D). 15 cents.

Highway Capacity Manual. 65 cents.

Highway Needs of the National Defense (House Document No. 249). 50 cents.

Highway Practice in the United States of America. 50 cents.

Highway Statistics, 1945. 35 cents.

Highway Statistics, 1946. 50 cents.

Highway Statistics, 1947. 45 cents.

Highway Statistics, 1948. 65 cents.

Highway Statistics, Summary to 1945. 40 cents

Highways of History. 25 cents.

Interregional Highways (House Document No. 379). 75 cents.

Legal Aspects of Controlling Highway Access. 15 cents.

Manual on Uniform Traffic Control Devices for Streets and Highways. 50 cents.

Principles of Highway Construction as Applied to Airports, Flight Strips, and Other Landing Areas for Aircraft. $1.50.

Public Control of Highway Access and Roadside Development. 35 cents.

Public Land Acquisition for Highway Purposes. 10 cents.

Roadside Improvement (No. 191MP). 10 cents.

Specifications for Construction of Roads and Bridges in National Forests and National Parks (FP-41). $1.25.

Taxation of Motor Vehicles in 1932. 35 cents.

The Local Rural Road Problem. 20 cents.

Tire Wear and Tire Failures on Various Road Surfaces. 10 cents.

Transition Curves for Highways. $1.25.

Single copies of the following publications are available to highway engineers and administrators for official use, and may be obtained by those so qualified upon request addressed to the Bureau of Public Roads. They are not sold by the Superintendent of Documents.

ANNUAL REPORTS

(See also adjacent column)

Public Roads Administration Annual Reports:
1943. 1944. 1945.

MISCELLANEOUS PUBLICATIONS

Bibliography on Automobile Parking in the United States.

Bibliography on Highway Lighting.

Bibliography on Highway Safety.

Bibliography on Land Acquisition for Public Roads.

Bibliography on Roadside Control.

Express Highways in the United States: a Bibliography.

Indexes to PUBLIC ROADS, volumes 17–19, 22, and 23.

Road Work on Farm Outlets Needs Skill and Right Equipment.

REPORTS IN COOPERATION WITH UNIVERSITY OF ILLINOIS

No. 304 . . . A Distribution Procedure for the Analysis of Slabs Continuous Over Flexible Beams.

No. 313 . . . Tests of Plaster-Model Slabs Subjected to Concentrated Loads.

No. 332 . . . Analyses of Skew Slabs.

No. 345 . . . Ultimate Strength of Reinforced Concrete Beams as Related to the Plasticity Ratio of Concrete.

No. 346 . . . Highway Slab-Bridges With Curbs: Laboratory Tests and Proposed Design Method.

No. 363 . . . Study of Slab and Beam Highway Bridges. Part I.

No. 369 . . . Studies of Highway Skew Slab-Bridges with Curbs. Part I: Results of Analyses.

No. 375 . . . Studies of Slab and Beam Highway Bridges. Part II.

No. 386 . . . Studies of Highway Skew Slab-Bridges with Curbs. Part II: Laboratory Research.

STATUS OF FEDERAL-AID HIGHWAY PROGRAM

AS OF JUNE 30, 1950

(Thousand Dollars)

STATE	UNPROGRAMMED BALANCES	ACTIVE PROGRAM											
		PROGRAMMED ONLY			PLANS APPROVED, CONSTRUCTION NOT STARTED			CONSTRUCTION UNDER WAY			TOTAL		
		Total Cost	Federal Funds	Miles	Total Cost	Federal Funds	Miles	Total Cost	Federal Funds	Miles	Total Cost	Federal Funds	Miles
Alabama	$13,615	$14,192	$7,145	419.7	$4,814	$2,343	156.7	$12,137	$6,295	269.1	$31,143	$15,783	845.5
Arizona	1,425	4,147	2,907	91.5	1,390	971	32.9	5,869	4,201	116.1	11,406	8,079	240.5
Arkansas	1,848	11,112	6,217	287.9	10,768	5,285	305.1	14,027	6,903	323.6	35,907	18,405	916.6
California	3,188	36,484	14,443	238.9	8,499	3,806	86.3	38,683	19,171	217.7	83,666	37,420	542.9
Colorado	3,026	5,603	3,107	128.7	2,919	1,716	96.3	15,611	9,020	300.9	24,133	13,843	525.9
Connecticut	2,323	10,434	5,050	25.3	2,024	982	7.1	6,564	3,797	8.3	19,022	9,829	40.7
Delaware	1,233	2,642	1,330	40.5	2,310	1,152	15.7	4,997	2,371	58.5	9,949	4,853	114.7
Florida	4,826	16,165	8,245	451.7	6,061	3,372	126.9	10,616	5,385	267.2	32,842	17,002	845.8
Georgia	4,139	15,903	8,259	417.6	6,425	3,212	191.0	41,454	19,684	731.8	63,782	31,155	1,340.4
Idaho	4,927	8,920	5,595	340.7	1,793	1,107	46.2	6,604	4,127	179.6	17,317	10,829	566.5
Illinois	18,808	47,642	24,815	367.4	20,409	10,184	166.8	48,597	23,364	353.7	116,648	58,363	887.9
Indiana	16,530	17,986	9,493	66.9	7,524	3,777	64.0	12,768	6,669	55.9	38,278	19,939	186.8
Iowa	3,283	13,397	5,958	607.1	6,834	2,654	351.7	20,595	9,997	758.9	40,826	18,609	1,717.7
Kansas	4,478	11,785	6,035	1,149.1	4,895	2,478	484.2	14,586	7,501	594.5	31,266	16,014	2,227.8
Kentucky	2,460	14,763	7,241	200.7	9,330	4,638	168.7	15,238	7,518	289.2	39,331	19,397	658.6
Louisiana	5,769	19,950	9,665	211.9	8,388	4,106	110.2	16,585	8,562	183.5	44,923	22,333	505.6
Maine	1,857	9,962	5,359	127.7	1,277	715	9.5	5,872	2,911	80.6	17,111	8,985	217.8
Maryland	2,007	7,577	3,656	29.0	2,921	1,199	27.3	17,007	8,211	61.4	27,505	13,066	117.7
Massachusetts	2,314	14,577	6,710	15.5	6,216	3,178	7.5	58,111	28,140	58.7	78,904	38,028	81.7
Michigan	6,969	17,459	9,032	599.6	9,526	4,754	264.0	43,284	17,877	203.6	70,269	31,663	1,067.2
Minnesota	2,370	12,049	6,356	1,124.3	11,154	5,796	761.6	19,902	10,484	513.1	43,105	22,636	2,399.0
Mississippi	10,938	5,824	2,924	301.2	2,871	1,436	130.2	6,183	3,249	196.9	14,878	7,609	628.3
Missouri	7,162	29,740	15,733	848.4	11,410	5,055	279.5	30,440	15,177	605.8	71,590	35,965	1,733.7
Montana	5,320	16,392	8,565	610.7	4,055	2,502	148.9	14,403	8,917	374.2	34,850	19,984	1,133.8
Nebraska	5,298	19,133	9,914	664.2	4,132	1,945	74.7	12,844	7,369	310.1	36,109	19,228	1,049.0
Nevada	1,637	5,474	4,514	190.1	221	180	3.2	5,330	4,366	188.4	11,025	9,060	381.7
New Hampshire	1,774	5,948	2,961	58.5	500	230	2.9	3,798	1,835	27.9	10,246	5,026	89.3
New Jersey	2,560	4,504	2,152	11.5	9,879	4,819	12.3	17,266	8,286	26.7	31,649	15,257	50.5
New Mexico	1,316	9,819	6,264	323.7	2,608	1,692	105.5	6,857	4,468	215.5	19,284	12,424	644.7
New York	34,159	72,813	37,264	231.4	23,018	10,349	43.7	92,013	45,635	185.6	187,844	93,248	460.7
North Carolina	3,460	22,659	10,893	571.0	5,962	2,854	182.8	19,715	9,468	470.9	48,336	23,215	1,224.7
North Dakota	3,942	8,059	4,182	1,390.5	4,401	2,202	273.3	9,714	4,883	672.9	22,174	11,267	2,336.7
Ohio	8,533	50,796	24,012	490.1	23,256	11,927	128.6	41,107	19,920	200.8	115,159	55,859	819.5
Oklahoma	957	22,835	12,527	301.9	11,596	5,374	342.2	14,887	7,267	405.1	49,318	25,168	1,049.2
Oregon	982	7,233	4,194	96.2	1,970	1,152	29.9	13,405	7,604	210.7	22,608	12,950	336.8
Pennsylvania	4,294	38,896	19,087	101.8	17,836	8,869	37.6	73,953	36,545	170.0	130,685	64,501	309.4
Rhode Island	121	9,662	4,918	63.8	1,577	768	2.4	10,172	5,077	7.5	21,411	10,763	73.7
South Carolina	3,104	9,303	4,585	272.1	1,488	797	106.6	12,146	6,084	492.5	22,937	11,466	871.2
South Dakota	1,294	12,632	7,322	1,190.2	4,174	2,533	367.2	7,350	4,503	568.7	24,156	14,358	2,126.1
Tennessee	1,140	15,259	7,393	329.3	11,892	5,466	335.2	18,342	8,506	337.3	45,493	21,365	1,001.8
Texas	9,854	6,223	3,176	428.1	12,296	6,452	552.5	56,277	25,630	1,667.2	74,796	35,258	2,647.8
Utah	1,588	5,179	3,800	177.7	1,590	1,151	62.9	5,677	4,147	119.8	12,446	9,098	360.4
Vermont	1,414	2,721	1,484	40.4	1,548	748	4.6	3,470	1,567	34.5	7,739	3,799	79.5
Virginia	5,502	25,786	12,916	561.4	5,112	2,533	150.7	15,653	7,626	277.3	46,551	23,075	989.4
Washington	1,898	13,256	6,086	132.9	3,329	1,619	98.4	19,100	8,721	126.9	35,685	16,426	358.2
West Virginia	2,146	16,905	7,251	180.7	2,006	1,011	35.9	10,228	5,122	65.1	29,139	13,384	281.7
Wisconsin	8,525	24,911	12,754	473.8	5,471	2,629	242.0	16,252	7,962	384.5	46,634	23,345	1,100.3
Wyoming	850	3,528	2,131	67.3	1,282	808	63.4	7,864	5,184	334.9	12,674	8,123	465.6
Hawaii	1,506	8,036	3,714	24.0	2,187	962	.5	4,190	1,952	21.3	14,413	6,628	45.8
District of Columbia	1,606	5,700	3,063	7.5	119	59	.5	396	198		6,215	3,320	8.0
Puerto Rico	5,615	4,069	1,819	17.0	1,435	662	6.3	10,842	4,575	47.5	16,346	7,056	70.8
TOTAL	245,890	796,044	404,216	17,099.1	314,698	156,209	7,304.1	988,981	494,031	14,372.4	2,099,723	1,054,456	38,775.6